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Florpyrauxifen-benzyl Activity and Use in Louisiana Rice Production

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FLORPYRAUXIFEN-BENZYL ACTIVITY AND USE IN LOUISIANA RICE PRODUCTION

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Abstract

Field studies were conducted in 2018 at two locations at the H. Rouse Caffey Rice Research Station (RRS) to evaluate the activity of titrated rates of florpyrauxifen-benzyl on aquatic weeds. Florpyrauxifen-benzyl was applied at 0, 3.6, 7.3, 11, 14.6, 18.3, 22, 25.6, and 29.5 g ai ha^{-1} into 91-cm diameter galvanized rings containing ducksalad, alligatorweed, cattail, creeping water primrose, grassy arrowhead, and pickerelweed. Ducksalad control was 89 to 99% when treated with all rates of florpyrauxifen at 11 to 29.5 g ha^{-1}; however, control was reduced to 51 to 79% when treated with rates lower than 11 g ha^{-1}.

Three field studies were conducted at the RRS in 2017 and 2018 evaluating the interactions of florpyrauxifen-benzyl mixed with graminicides, ALS-inhibiting, or contact herbicides. Little to no antagonistic interactions were observed for barnyardgrass treated with florpyrauxifen mixed with graminicides. Antagonistic interactions were observed for barnyardgrass activity when treated with florpyrauxifen mixed with all ALS-inhibiting and contact herbicides. Severely antagonistic interactions were indicated by barnyardgrass treated with florpyrauxifen mixed with propanil or orthosulfamuron.

Field studies were conducted in 2017 and 2018 to evaluate the activity of florpyrauxifen-benzyl and a prepackaged mixture of halosulfuron plus prosulfuron compared with other products applied at a late-season salvage timing. At 42 DAT, yellow nutsedge, hemp sesbania, and Indian jointvetch control was greater than 97% when treated with halosulfuron at 53 g ai ha^{-1}. A similar response was observed for these weeds when treated with florpyrauxifen-benzyl or halosulfuron plus prosulfuron. Alligatorweed control was 99% when treated with florpyrauxifen at 29 g ha^{-1}. Similar control was observed with florpyrauxifen applied at 14.5 g ha^{-1}. Similar

control was observed at 42 DAT when alligatorweed was treated with halosulfuron plus prosulfuron at 55 or 83 g ai ha^{-1}.

Chapter 1
Introduction

Rice (*Oryza sativa* L.) is a staple in the diet for approximately half of the world's population and supplies 20% of calories consumed worldwide (Kubo and Purevdorj 2004). As the world's largest food crop, rice has supported a greater number of people for a longer period of time than any other crop since it was domesticated in China between 8000 and 10000 years ago (Greenland 1997; Sweeney and McCouch 2007). Rice cultivation in the United States began in the tidewater regions of the Carolina colonies in 1685 and has since expanded to Arkansas, California, Louisiana, Mississippi, Texas, and Missouri (Smith and Dilday 2003; USDA NASS 2020). In 2019, rice was planted on approximately 172,000 hectares in Louisiana, the third largest rice producing state in the United States (USDA NASS 2020). The majority of rice in Louisiana is produced in the northeast and southwest regions of the state; however, cultural management for production in these two areas can differ primarily due to differences in soil type, weather conditions, weed species, and tradition (Bollich 1992).

In Louisiana, both dry- and water-seeded planting practices are commonly utilized (Harrell and Saichuk 2014). Dry-seeding by either drilling or broadcast is the predominant planting method statewide; however, in 2016 an estimated 35% of the rice produced in the southwest region was water-seeded with the remainder dry-seeded (Harrell 2016). Prior to the introduction of imidazolinone-resistant (IR) rice in 2002, an estimated 65 to 70% of Louisiana rice was water seeded (Eric Webster, LSU AgCenter Extension Weed Scientist, personal communication). Using this planting method, pre-germinated rice seed is broadcast into floodwater, which is held on the field most of the growing season to create an environment that is not favorable for red rice (*Oryza sativa* L.) or other weed seed germination (Dunand et al.

1985). In addition to red rice management, water-seeding can be utilized as an alternative planting practice when excessive rainfall inhibits or prohibits dry-seeding (McKnight 2017).

Water-seeded rice production typically involves three different flooding systems: delayed, pinpoint, and continuous (Harrell and Saichuk 2014). In the delayed flood system, fields are drained following seeding for a period of 3- to 4-weeks before the permanent flood is established. This system is common where red rice does not present a problem and fertilizer and herbicide application timings are similar to dry-seeding after the initial drain. Pinpoint flooding is the most common water-seeding method and the permanent flood is established much earlier than delayed flooding. After seeding, the field is drained briefly to allow the developing rice radicle to penetrate the soil and anchor the seedling. A 3- to 5-day period after the initial drain is usually sufficient before the flood is re-established. Continuously flooded rice remains flooded from seeding until draining prior to harvest; however, this system is limited in Louisiana because rice stand establishment can be an issue, even for the cultivars with high seedling vigor.

Louisiana was first known for its crawfish [*Procambarus clarkii* (Girard); *Procambarus zonangulus* (Hobbs & Hobbs)] capture fishery as early as the 18th century, where recreational and commercial fishermen harvested crawfish from the extensive wetlands of the lower Mississippi River floodplain (McClain and Romaire 2004). Commercialization of crawfish production began in the 1950s, when rice-producing land was also used in conjunction with crawfish aquaculture. The integration of crawfish aquaculture with rice culture has proven to be a successful rotational system in Louisiana. As with water seeding, these rotations result in extended field inundation periods; thus, creating a more favorable environment for aquatic plant growth, development, and interference with rice production. Several weed species such as ducksalad [*Heteranthera limosa* (Sw.) Willd.], grassy arrowhead (*Sagittaria graminea* Michx.

var. *graminea*), pickerelweed (*Pontederia cordata* L.), creeping burhead [*Echinodorus cordifolius* (L.) Griseb.], and common cattail (*Typha latifolia* L.) are dependent on aquatic environments for survival and can interfere with rice production, especially where crawfish was produced in the previous year (McKnight 2017; Webster 2014).

The implementation of integrated weed management programs through the use of cultural, mechanical, or chemical methods is crucial to maximize yield and economic returns for rice producers (Jordan and Sanders 1999). In 2012, approximately 73% of farm land in the United States received a herbicide application (USDA 2012). Ashton and Monaco (1991) estimated farmers spend 3.6 billion dollars annually for chemical weed control; however, 16 years later Gianessi and Reigner (2007) reported and estimated annual herbicide costs of 7 billion dollars. Consequently, herbicide-resistant weeds have become an issue for rice production in the United States. Several examples have been documented in Louisiana, such as barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv] resistant to propanil (Carey et al. 1995), quinclorac (Malik et al 2010), and imazethapyr (Riar et al. 2013). In addition, rice flatsedge (*Cyperus iria* L.) (Riar et al. 2015) and yellow nutsedge (*Cyperus esculentus* L.) (Tehranchian et al. 2015) resistance to ALS-inhibiting herbicides also presents a weed management issue for rice producers.

The utilization of herbicides with alternative modes of action would serve as an additional component to an overall weed resistance management program (Norsworthy et al. 2012). Florpyrauxifen-benzyl was released for use in 2018, representing a new structural class of synthetic auxin herbicides in the arylpicolinate family to be used in rice and crawfish production (Loyant™ herbicide with Rinskor™ active, Corteva Agriscience™, Indianapolis, IN). Unlike other synthetic auxin herbicides such as 2,4-dichlorophenoxy acetic acid (2,4-D), florpyrauxifen-benzyl exhibits strong binding affinity for different auxin signaling F-box proteins than other synthetic auxin herbicides, signifying a unique mechanism of action (Bell et al. 2005; Epp et al. 2016; Jeschke 2015b). Florpyrauxifen-benzyl must be metabolically converted to florpyrauxifen-acid in weeds through enzymatic hydrolysis; therefore, increased soil moisture conditions play a significant role in the conversion of this herbicide to its active form for grass and sedge management (Jeschke 2015a; Epp et al. 2016; Miller and Norsworthy 2018b). Miller and Norsworthy (2018b) reported approximately half of florpyrauxifen-benzyl applied at 7.5% soil moisture was absorbed by barnyardgrass and yellow nutsedge, compared with 86 to 97% absorption at 60% soil moisture. In addition, only 61 to 67% of florpyrauxifen-benzyl applied to barnyardgrass and yellow nutsedge was metabolically converted to florpyrauxifen-acid in low soil moisture conditions compared with 83% conversion by hemp sesbania [*Sesbania herbaceae* (Mill.) McVaugh], a broadleaf weed.

Florpyrauxifen-benzyl is in the arylpicolinate family of herbicides and exhibits broad spectrum activity on broadleaf, grass, and sedge weeds, which is atypical of other synthetic auxin herbicides (Miller and Norsworthy 2018a). Synthetic auxin herbicides in the phenoxycarboxylic acid family, such as 2,4-D, have been used to manage broadleaf weeds since the 1940s with little to no grass activity (Grossman 2010). Similarly, dicamba is a synthetic auxin herbicide in the benzoic acid family used for broadleaf weed control in corn, cotton, and soybean (Shaner 2014). Triclopyr is in the pyridinecarboxylic acid family and is used for broadleaf management in rice. Quinclorac, an auxin herbicide in the quinoline carboxylic acid family, has activity on broadleaf and grass weeds in rice and turfgrass; however, quinclorac has little to no activity on sedges and barnyardgrass resistance can be problematic (Malik et al. 2010; Shaner 2014).

Herbicide mixtures are an integral component of weed management programs with regards to improving herbicide activity, broadening the weed control spectrum, and maximizing yield and economic returns (Carlson et al. 2011; Pellerin et al. 2003; Pellerin and Webster 2004; Webster et al. 2012). Herbicides applied in mixtures often have different modes of action, and plants treated with mixtures will indicate one of three responses: antagonistic, synergistic, or neutral (Berenbaum 1981; Blouin 2010; Fish et al. 2015, 2016; Hatzios and Penner 1985; Morse 1978; Nash 1981; Rustom et al. 2018, 2019; Webster et al. 2019). Herbicide antagonism is defined by Beste (1983) as "an interaction of two or more chemicals such that the effect when combined is less than the predicted effect based on each chemical applied separately." Synergism is the inverse of antagonism, where the effect when combined exceeds the predicted effect based on the herbicides applied separately. An additive or neutral response is indicated by similar effects when herbicides are applied combined or alone.

Historically, herbicides with grass activity are often antagonized by other herbcides (Blackshaw et al. 2006; Rustom et al. 2018, 2019; Scherder et al. 2005; Webster et al. 2019; Zhang et al. 2005). Webster et al. (2019) suggested synthetic auxin herbicides such as 2,4-D, triclopyr, and quinclorac antagonize quizalofop activity. In addition, auxin herbicides such as triclopyr have been reported to antagonize fenoxaprop and cyhalofop activity on barnyardgrass (Scherder et al. 2005; Zhang et al. 2005). Additionally, Blackshaw et al. (2006) observed quizalofop antagonism by 2,4-D amine applied on volunteer wheat (*Triticum aestivum* L.) seedlings. Quizalofop activity can also be antagonized when mixed with ALS-inhibiting herbicides such as penoxsulam or bispyribac, or contact herbicides such as propanil for red rice (*Oryza sativa* L.) control (Rustom et al. 2018, 2019). However, Fish et al. (2015) reports red rice treated with imazethapyr, an ALS herbicide, plus and propanil indicated a synergistic response.

Statistically, herbicide mixtures are typically evaluated using Colby's (1967) linear model to determine a synergistic, antagonistic, or additive/neutral response. Using this procedure, an expected response is calculated based on the activity of the herbicides applied alone, then compared to an observed response. Blouin (2004) suggested the expected response is a nonlinear function of the means for the herbicides applied alone, then the standard linear model methodology for tests of hypotheses does not apply; therefore, the Blouin et al. (2004) nonlinear mixed-model is more sensitive than Colby's linear model in detecting synergistic or antagonistic interactions. Blouin et al. (2010) further modified the nonlinear model into an augmented mixed-model, which proved to be more sensitive than the Blouin et al. (2004) nonlinear mixed model when observing fenoxaprop-p-ethyl mixtures with various rice herbicides.

It is well known that one of the primary benefits of flooding rice is weed control, considering rice tolerates hypoxic conditions better than most weeds (Helms 1994; Masson et al. 2001; Smith et al. 1977). As with other crops, rice weed management programs should be designed to manage weeds early in the growing season; however, situations may arise where this approach cannot be sustained until the rice is flooded (Bond and Walker 2012; Page et al. 2012; Smith 1968, 1988). Postflood salvage treatments are problematic because of the advanced growth stage of target weeds and poor spray coverage from the developing rice canopy (Bond and Walker 2012). Typical salvage situation herbicides in Louisiana include halosulfuron for broadleaf and sedge management and cyhalofop or fenoxaprop for grass management (Eric Webster, LSU AgCenter Extension Weed Scientist, personal communication). The potential for ALS-resistant sedges or ACCase antagonism previously described can further complicate postflood salvage treatments.

Florpyrauxifen-benzyl could play an integral role in Louisiana rice weed management programs. Understanding the activity of this new technology in several different rice production situations is imperative before developing these programs. Since florpyrauxifen-benzyl has activity on grasses and sedges, the potential exists for either synergism or antagonism by other herbicides. Likewise, it is important to understand the impact florpyrauxifen-benzyl has on other herbicides with grass activity. Considering florpyrauxifen-benzyl activity is increased with soil moisture, this new technology could potentially be used for aquatic weed management in both rice and crawfish production systems and in postflood salvage situations where weed control may be more difficult. Therefore, the overall objective of this research is to evaluate the activity of florpyrauxifen on emergent aquatic weeds, in a salvage situation, mixed with other herbicides labeled for use in rice production.

Chapter 2
Aquatic Weed Response to Titrated Rates of Florpyrauxifen-benzyl

Introduction

Rice (*Oryza sativa* L.) is a summer annual known for its adaptation to aquatic environments that is produced in at least 95 countries worldwide and is a major caloric source for a large portion of the earth's population (Smith and Dilday 2002). Louisiana is the third largest rice producing state in the United States, planting approximately 175,000 hectares (ha) in 2019 with an average yield of 8290 kg ha^{-1} (USDA NASS 2020). Most of the rice in Louisiana is grown in the southwest and northeast areas of the state; however, crop rotations, cultural practices, soil type, weather, weed species, and tradition can vary greatly between the two regions (Bollich 1992).

Both dry- and water-seeded planting practices are employed in Louisiana rice production (Harrell and Saichuk 2014). Prior to 2002, approximately 65 to 70% of Louisiana rice was water-seeded primarily to control red rice (*O. sativa* L.) (Eric Webster, LSU AgCenter Extension Weed Scientist, personal communication). However, the discovery and development of imidazolinone-resistant (IR) rice in 1993 provided a more economical means of chemical weed management for red rice control (Carlson et al. 2012; Croughan 1994; Webster and Masson 2001). Since the development of IR rice, dry-seeding by either drill or broadcast is the predominant planting method statewide; however, in 2016 an estimated 35% of the rice produced in the south Louisiana was water-seeded with the remainder dry-seeded (Harrell 2016).

Water-seeded rice production typically involves three different flooding systems: delayed, pinpoint, and continuous (Harrell and Saichuk 2014). In the delayed flood system, fields are drained following seeding for a period of 3- to 4-weeks before the permanent flood is established. This system is common where red rice does not present a problem and fertilizer and herbicide application timings are similar to dry-seeding after the initial drain. Pinpoint flooding is the most common water-seeding method, and the permanent flood is established much earlier than delayed flooding. After seeding, the field is drained briefly to allow the developing rice radicle to penetrate the soil and anchor the seedling. A 3- to 5-day period after the initial drain is usually sufficient before the flood is re-established. Continuously flooded rice remains flooded from seeding until draining prior to harvest; however, this system is limited in Louisiana because rice stand establishment can be an issue, even for the cultivars with high seedling vigor.

Crawfish [*Procambarus clarkii* (Girard); *Procambarus zonangulus* (Hobbs & Hobbs)] aquaculture production systems are often implemented in rotation with rice production (McClain and Romaire 2004). The crawfish capture fishery originated in Louisiana as early as the 18th century. In the 1950s, commercialization of crawfish production resulted in the integration of crawfish aquaculture with rice-producing agricultural land, which has proven to be a successful rotational system in Louisiana. Crawfish harvest begins as early as mid-November and continues through June (Romaire et al. 2004). Rice is typically planted in March and April and harvested as early as July for the first crop and late fall for the second crop (Harrell and Saichuk 2014). Therefore, it is not uncommon for fields to be under flooded conditions for the majority of the year in south Louisiana.

Flooding has historically served as a beneficial weed management tool for rice production; however, changes in plant population dynamics are largely driven by changes in in the environment (Crawley 1990). Coupled with water seeding, these rice-crawfish rotations result in extended field flood inundation periods; thus, creating a more favorable environment for aquatic weed growth, development, and interference (Jackson and Colmer 2005; McKnight 2017; Webster 2014). Furthermore, lack of tillage can contribute to the shift from annual grass and broadleaf weeds to perennial aquatic weeds (Webster 2014). Several aquatic weeds that interfere with rice productivity in Louisiana are alligatorweed [*Alternanthera* philoxeroides (Mart.) Griseb], ducksalad [*Heteranthera limosa* (Sw.) Willd.], grassy arrowhead (*Sagittaria graminea* Michx. var. *graminea*), pickerelweed (*Pontederia cordata* L.), creeping water primrose [*Ludwigia peploides* (Kunth) P.H. Raven], and common cattail (*Typha latifolia* L.).

Alligatorweed is a decumbent perennial invasive weed that is a member of the Amaranthaceae family and a native to South America that can grow up to 1 m tall (Bryson and Delfice 2009). Generally, alligatorweed does not produce seeds and reproduces by vegetative means by rooting at each node. Stems are hollow, simple or branched, and glabrous except for few trichomes at the leaf base. Leaves are opposite, glabrous, linear-elliptic, tips acute, with a distinctive midrib. Inflorescences are solitary, white, 13-mm diameter, axillary or terminal, and 6- to 20-florets per head, each with 5-stamens. Alligatorweed is found in all Louisiana parishes and has been considered one of the 10 most troublesome weeds in Louisiana rice production (Willingham et al. 2015; Webster et al. 2003).

Ducksalad is an annual aquatic weed native to the Americas that is tufted; however, this plant can act as an annual in certain environments by spreading from rhizomes rooted in moist to saturated soil (Bryson and Delfice 2009). Commonly found in wet cultivated areas such as rice fields, this aquatic weed has erect, fleshy, stems that tend to root at the nodes and can grow up to 15-cm tall. Leaf blades are up to 10-cm long, linear to oblanceolate, including a petiole up to 6 cm long and 0.4 to 3.3 cm wide, narrowed to acute, obtuse, or slightly heart-shaped base (Bryson and Delfice 2009; Webster 2014). Each inflorescence has one white or blue flower with 15-to 44-mm tubes and smooth spathes 0.9- to 4.5-cm long (Bryson and Delfice 2009). Seeds are 0.5- to 0.8-mm long, 0.2-to 0.6-mm wide, black to gray, reticulate, and ribbed. Ducksalad is found in all Louisiana parishes and can germinate and emerge through a permanent flood, often becoming a problem in water-seeded rice (McKnight 2017; Smith 1968; Webster 2014).

Grassy arrowhead is a perennial aquatic weed with short, stout rhizomes native to North America that can grow up to 50-cm tall (Bryson and Delfice 2009). Stems are erect and unbranched from the rhizome, except at the lowest node. Leaves are on long, spongy petioles and linear to linear-lanceolate to elliptic. Inflorescences are pistillate in the lower one- to two-whorls and staminate above, flower stalks are spreading or ascending but not recurved, and petals are white. Webster (2014) reports *Sagittaria* sp. occur in all Louisiana parishes in wetlands, ditches, flooded rice fields, and pond edges.

Pickerelweed is an aquatic herbaceous perennial in the Pontederiaceae family that can grow up to 1.2-m tall (Bryson and Delfice 2009). A native to North America, this monocot produces thick, enlarged, fibrous roots from nodes along a thick, submerged rhizome. Leaves are emergent, basal, arising from sheaths, 7- to 20-cm long, ovate to lanceolate, cordate-saggitate, narrowed at the base, 5- to 30-cm petiole, and glandular-pubescent. Inflorescences are emergent in dense, elongated spike 5- to 15-cm long with 6-petaloid tepals, funnelform below to form a nonfused corolla tube, upper corolla lobe with a reniform yellow patch, subtended by a pair of bracts, and covered by glandular trichomes. Seeds are reddish-brown, glutinous, ovoid, 3- to 4-mm long, and 2 to 2.5 mm wide. Similar to grassy arrowhead distribution in Louisiana, pickerelweed is found in all parishes including wetlands, ditches, flooded rice fields, and pond edges (Webster 2014).

Creeping water primrose is a perennial that roots at the nodes and can form dense mats in shallow water (Bryson and Delfice 2009). Leaves are glabrous or sparsely short-pubescent, alternate, 1- to 8-cm long, elliptic to obovate on young shoots, oblanceolate to spatulate on lower branches, and lanceolate to narrowly elliptic and larger on the distal portions. Inflorescences are solitary in axils of the upper leaves and glabrous or occasionally sparsely pubescent. Flowers contain 5 yellow obovate petals 10- to 15- mm long. The calyx is 5-segmented, 8- to 12- mm long, and are usually glabrous with few long trichomes. Like grassy arrowhead and pickerelweed distribution, Webster (2014) reported creeping water primrose is found in all Louisiana parishes.

Common cattail is a perennial emergent aquatic native to North America with large, creeping rhizomes that can often form dense colonies and can grow up to 3-m tall (Bryson and Delfice 2009). This grass-like monocot is a member of the Typhaceae family with linear, thick flattened, and firm but spongy leaves. Inflorescences contain staminate flowers above pistillate flowers on spikes that can be contiguous to 2.5-cm apart. The staminate spike can be 4- to 16-cm long with reduced stamens and the pistillate spike 5- to 20-cm long, thicker towards the base, stipitate, unilocular superior ovaries with stipes bearing slender bristles. Cattail commonly interferes with rice production in the United States, Greece, India, Iran, Mexico, Portugal, and the Philippines (Holm et al. 1997; Mitich 2000).

In 2018, Corteva Agriscience™ released florpyrauxifen-benzyl (florpyrauxifen), a new structural class of arylpicolinate herbicides with auxin-mimicing activity. Florpyrauxifen exhibits a binding affinity in plants that is atypical of other auxin herbicides used for broadleaf weed management; therefore, this herbicide represents a new mechanism of action with activity on broadleaf, grass, and sedge weeds (Bell et al. 2005; Epp et al. 2016; Jeschke 2015b; Miller and Norsworthy 2018a). Furthermore, this new product is labeled for use in both rice and crawfish production (Anonymous 2017).

Florpyrauxifen must be metabolically converted by plants to florpyrauxifen-acid through enzymatic hydrolysis to become active; therefore, soil moisture conditions have a significant impact on the activity of this product (Jeschke 2015a; Epp et al. 2016; Miller and Norsworthy 2018b). Miller and Norsworthy (2018b) reported approximately half of florpyrauxifen applied at 7.5% soil moisture was absorbed by barnyardgrass and yellow nutsedge, compared with 86 to 97% absorption at 60% soil moisture. In addition, only 61 to 67% of florpyrauxifen applied to barnyardgrass and yellow nutsedge was converted to florpyrauxifen-acid in low soil moisture conditions compared with 83% conversion by hemp sesbania [*Sesbania herbaceae* (Mill.) McVaugh].

Florpyrauxifen is a beneficial tool for producers to control a broad spectrum of weeds in rice and crawfish production; however, little research has been conducted to evaluate the activity of this herbicide on aquatic weeds commonly found in these production systems. Given the increased activity of florpyrauxifen under high soil moisture conditions on a broad spectrum of weeds (Miller and Norsworthy 2018b), this herbicide could potentially be useful to manage the aquatic weeds commonly found infesting rice and crawfish production in Louisiana, especially in areas where crawfish production and/or water-seeded rice rotations are common. Therefore, the objective of this research is to evaluate the activity of florpyrauxifen when applied at titrated rates on emergent aquatic weeds commonly found in Louisiana rice.

Materials and Methods

A field study was conducted in 2018 at two locations at the H. Rouse Caffey Rice Research Station (RRS) near Crowley, Louisiana to evaluate aquatic weed responses to titrated rates of florpyrauxifen. The soil type for one study location at the RRS soil type at the RRS is a Crowley silt loam (fine smectic, thermic Typic Albaqualfs) with a pH of 6.4, 1.4% organic matter, and planted April 19. The soil type at the second location was a Midland silty clay loam (fine, smectitic, thermic Chromic Vertic Epiaqualf) with a pH of 6.1, 1.2% organic matter, and planted May 7. Field preparation consisted of a fall and spring disking followed by (FB) two passes in opposite directions with a two-way bed conditioner consisting of rolling baskets and S-tine harrows set at 6 cm depth.

The experimental design for the study was a randomized complete block. Following seedbed preparation, 1.5- by 5.2-m plots were established and one 91-cm diameter by 30-cm tall galvanized ring was placed in the center of each plot and pressed firmly into the soil to a depth of 5-cm to seal and isolate the area contained inside the ring from the rest of the plot area. Sekino et al. (2008) and Mcknight et al. (2018) utilized similar rings to provide herbicide containment without the need for individually leveed plots. Water management mimicked a pinpoint water-seeded rice production system; however, no rice was planted in the plot area. Lack of competition between the weeds and rice allows the full effect of the herbicide treatment to be evaluated without interference from shading or resource competition. Fertility and other pest management practices were based on the LSU AgCenter Rice Production Guidelines (Harrell and Saichuk 2014).

After ring placement, aquatic weeds were transplanted into each ring at a rate of 2 plants species^{-1} in each ring. Approximately 2 weeks after transplanting, the weeds were trimmed level with the floodwater to promote similar amounts of new vegetative growth for each species in all rings. The research area was also naturally infested with ducksalad at 100- to 200-plants m^{-2}, florpyrauxifen was applied at a rate of 0, 3.6, 7.3, 11, 14.6, 18.3, 22, 25.6, and 29.5 g ai ha^{-1} when the ducksalad reached 8- to 12- cm tall at the first elongated leaf growth stage. In addition, alligatorweed was 25- to 50-cm tall with 15- to 40-leaves, grassy arrowhead was 10- to 20-cm tall with 2- to 4-leaves, pickerelweed was 15- to 30-cm tall with 2- to 4-leaves, creeping water primrose was 20- to 30-cm tall with 15- to 25-leaves, and cattail was 20- to 35-cm tall with 3- to

5-leaves at the time of application. All florpyrauxifen treatments included a methylated seed oil (MSO, Leci-Tech, Loveland Products, Loveland, CO) at a rate of 1% v/v. Applications were made using a CO_2-pressurized backpack sprayer calibrated to deliver 140-L ha^{-1} at 140 kPa with 5 flat fan 110015 nozzles spaced at 35 cm.

Visual weed control evaluations were recorded as a percent, with 0 = no control and 100 = complete plant death at 14, 28, 42, and 56 days after treatment (DAT). At 56 DAT, all dead or alive weed biomass above the soil surface from each ring was hand-harvested, separated by species, and weighed immediately. Control and biomass data were arranged as repeated measures and subject to the MIXED procedure of SAS (release 9.4, SAS Institute, Cary, NC). Location, replications (nested within treatments), and all interactions containing any of these effects were considered random effects. Considering year or combination of years as a random effect accounts for different environmental conditions each year having an effect on herbicide treatments for that year (Carmer et al. 1989; Hager et al. 2003).Herbicide treatment and evaluation timing were considered fixed effects. Type III statistics were used to test possible interactions of fixed effects using the UNIVARIATE procedure of SAS and significant normality problems were not observed. Tukey's honestly significant difference test was used to separate means at the 5% probability level ($P \leq 0.05$).

Results and Discussion

A herbicide application rate main effect occurred for alligatorweed control (Table 2.1); therefore, data were averaged over 14, 28, and 42 DAT. Control for alligatorweed treated with florpyrauxifen at the highest rate of 29.5 g ha^{-1} was 98%. A similar response was observed when alligatorweed was treated with florpyrauxifen at 25.6, 22, and 18.6 g ha^{-1}. However, control was reduced to 51 to 84% when treated with the 3.6 to 14.3 g ha^{-1} rates of florpyrauxifen. These data suggest that reducing the florpyrauxifen rate from 29.5 to 18.6 g ha^{-1} will result in similar activity for alligatorweed control. In addition, alligatorweed biomass reduction was similar to control data when treated with the same rates. Other research has suggested this activity will be similar to other auxin herbicides historically used to manage alligatorweed in rice production such as 2,4-D and triclopyr (Blackburn 1963; Hofstra and Champion 2010).

Table 2.1. Alligatorweed and ducksalad control and biomass reduction when treated with florpyrauxifen applied at titrated rates averaged over 14, 28, 42, and 56 DAT evaluation timings at two different locations in 2018.[a]

Florpyrauxifen	Alligatorweed		Ducksalad	
	Control[b]	Biomass[c]	Control	Biomass
g ai ha^{-1}	—— % ——	— % Reduction —	—— % ——	— % Reduction —
3.6	51 e	52 c	51 c	25 c
7.3	67 d	64 bc	79 b	85 b
11	78 cd	68 bc	89 ab	91 ab
14.3	84 bc	74 bc	95 a	99 a
18.6	90 abc	76 ab	97 a	99 a
22	92 ab	79 a	98 a	99 a
25.6	95 ab	84 a	98 a	99 a
29.5	98 a	86 a	99 a	99 a

[a]Means followed by a common letter do not significantly differ at P = 0.05 using Tukey's honestly significant difference test within columns.

[b]Control was measured using a scale of 0 = no control and 100= complete plant death based on visual symptoms.

[c]Reduction in biomass relative to the nontreated. Biomass was 307 and 1871 g for alligatorweed and ducksalad, respectively.

Similar to alligatorweed, a herbicide application rate main effect occurred for ducksalad control (Table 2.1); therefore, data were averaged over 14, 28, and 42 DAT evaluation timings. Ducksalad control was 89 to 99% when treated with all rates of florpyrauxifen at 11 to 29.5 g ha^{-1}; however, control was reduced to 51 to 79% when treated with rates lower than 11 g ha^{-1}. A similar trend was observed when ducksalad fresh weight biomass was reduced 91 to 99% when treated with florpyrauxifen at 11 to 29.5 g ha^{-1}. These data indicate rates as low as 11 g ha^{-1} will have the same impact on ducksalad as the maximum labeled single application rate of 29.5 g ha^{-1}. McKnight et al. (2018) reported similar activity on ducksalad treated with benzobicyclon applied at reduced rates.

A herbicide application rate by evaluation timing interaction occurred for cattail control (Table 2.2). At 14 DAT, cattail control was 81 and 91% when treated with 25.6 and 29.5 g ha^{-1}, respectively; however, cattail control was reduced to 69% when treated with 22 g ha^{-1}. However, by 28 DAT, cattail control was 85% when treated with florpyrauxifen at 22 g ha^{-1}, similar to cattail treated with 25.6 and 29.5 g ha^{-1}. A similar response was observed at 42 and 56 DAT, suggesting florpyrauxifen applied at 22 g ai ha^{-1} will have similar activity on cattail as the maximum labeled single application rate of 29.5 g ha^{-1}. Similarly, at 56 DAT cattail biomass was reduced by 89 to 98% compared with the nontreated when treated with florpyrauxifen at 22, 25.6, or 29.5 g ha^{-1}. Similar to the control data observed for cattail, these biomass data suggest cattail should be treated with florpyrauxifen at no less than 22 g ai ha^{-1}. In addition, Smith and Shaw (1966) suggested no herbicide will selectively control cattails and not injure rice; however, these data suggest florpyrauxifen can be used for cattail management in rice production.

Similar to cattail, a herbicide application rate by evaluation timing interaction occurred for creeping water primrose control (Table 2.3). Control for creeping water primrose treated with florpyrauxifen at 29.5 g ha^{-1} did not exceed 50% at any evaluation timing. At 28 and 42 DAT, creeping water primrose control was 41 to 48% when treated with florpyrauxifen at 25.6 g ha^{-1} or 29 g ha^{-1}. By 56 DAT, control was similar to the 29.5 g ha^{-1} rate when creeping water primrose was treated with florpyrauxifen at 25.6 and 22 g ha^{-1} at 43 and 41%, respectively. These control data suggest creeping water primrose growth and can be suppressed when treated with florpyrauxifen at 22, 25.6, or 29.5 g ha^{-1}; however, control of creeping water primrose never

Table 2.2. Cattail control when treated with florpyrauxifen at titrated rates at 14, 28, 42, and 56 DAT evaluation timings and biomass reduction at two different locations in 2018.[a]

	Cattail control[c]				
Florpyrauxifen	14 DAT	28 DAT	42 DAT	56 DAT	Biomass[b]
g ai ha^{-1}	%				%
3.6	15 l-o	13 no	10 o	14 mno	1 d
7.3	29 j-n	29 j-n	31 j-m	24 k-o	1 d
11	46 hij	46 hij	39 ijk	33 jkl	35 cd
14.3	51 ghi	68 c-g	63 e-h	59 fgh	55 bc
18.6	63 d-h	73 b-f	70 c-f	70 c-f	63 bc
22	69 c-f	85 abc	85 abc	79 a-e	89 ab
25.6	81 a-d	89 ab	88 ab	89 ab	97 a
29.5	91 ab	91 ab	93 a	93 a	98 a

[a]Means followed by a common letter do not significantly differ at P = 0.05 using Tukey's honestly significant difference test.

[b]Reduction in cattail biomass relative to the nontreated at 288 g. A separate Tukey's honestly significant difference test was used to analyze biomass at P = 0.05.

[c]Control was measured using a scale of 0 = no control and 100= complete plant death based on visual symptoms.

Table 2.3. Creeping water primrose control when treated with florpyrauxifen at titrated rates at 14, 28, 42, and 56 DAT evaluation timings and biomass reduction at two different locations in 2018.[a]

	Creeping water Primrose control[c]				
Florpyrauxifen	14 DAT	28 DAT	42 DAT	56 DAT	Biomass[b]
g ai ha^{-1}	%				g
3.6	11 op	11 op	10 op	7 p	22 de
7.3	16 m-p	21 j-n	18 l-o	15 nop	23 cde
11	19 k-o	26 h-m	24 i-n	15 nop	8 e
14.3	24 i-n	30 f-j	28 f-k	24 h-n	10 e
18.6	28 f-l	34 d-h	33 e-i	26 g-l	24 cde
22	29 f-j	36 c-g	38 b-f	41 a-e	44 ab
25.6	37 b-f	43 a-e	41 a-e	43 a-d	43 ab
29.5	45 ab	48 a	47 ab	50 a	62 a

[a]Means followed by a common letter do not significantly differ at P = 0.05 using Tukey's honestly significant difference test.

[b]Reduction in creeping water primrose biomass relative to the nontreated at 385 g. A separate Tukey's honestly significant difference test was used to analyze biomass at P = 0.05.

[c]Control was measured using a scale of 0 = no control and 100= complete plant death based on visual symptoms.

exceeded 50%. At 56 DAT, similar to creeping water primrose control data, biomass was reduced 44 to 62%. However, biomass increased when treated with florpyrauxifen at less than 22 g ha^{-1}. Sears et al. (2006) suggested triclopyr, another auxin herbicide labeled in rice, is an effective tool for management of creeping water primrose and may be a better option if this weed is present.

Similar to cattail and creeping water primrose control, a herbicide application rate by evaluation timing interaction occurred for grassy arrowhead control (Table 2.4). Grassy arrowhead control was 98 to 99% at all rating dates when treated with florpyrauxifen at 29.5 g ha^{-1}. In comparison, control was 87 to 89% at all evaluations when treated with 11 g ha^{-1}, similar to what was observed at the highest rate of 29.5 g ha^{-1}. However, control was reduced when treated with the lower rates of florpyrauxifen at 7.3 and 3.6 g ha^{-1}. A similar response was observed when grassy arrowhead fresh weight biomass was reduced 91 to 99% when treated with all rates between 11 and 29.5 g ha^{-1}. These data suggest florpyrauxifen applied at rates between 11 and 29.5 g ha^{-1} will have similar activity on grassy arrowhead. Young et al. (2015) reported similar activity on California arrowhead (*Sagittaria montevidensis* Cham. & Schltdl.), a taxonomic relative to grassy arrowhead, when treated with benzobicyclon.

Similar to cattail, creeping water primrose, and grassy arrowhead control, a herbicide rate by evaluation timing occurred for pickerelweed control (Table 2.5). At 14 DAT, pickerelweed control was 88 to 98% when treated with florpyrauxifen at 18.6 to 29.5 g ha^{-1}, with no differences observed. A similar response was observed at 28, 42, and 56 DAT for pickerelweed treated with rates of florpyrauxifen at 14.3 g ha^{-1} or higher. However, activity of florpyrauxifen on pickerelweed was reduced when treated with rates below 14.3 g ha^{-1}. A similar response was observed when pickerelweed biomass was reduced by 86 to 99% when treated with

Table 2.4. Grassy arrowhead control when treated with florpyrauxifen at titrated rates at 14, 28, 42, and 56 DAT evaluation timings and biomass reduction at two different locations in 2018.[a]

	Grassy Arrowhead control[c]				
Florpyrauxifen	14 DAT	28 DAT	42 DAT	56 DAT	Biomass[b]
g ai ha^{-1}	%				g
3.6	29 e	16 f	14 f	13 f	25 c
7.3	78 bcd	79 bcd	73 cd	69 d	85 b
11	87 a-d	88 abc	89 abc	88 abc	91 ab
14.3	92 ab	94 ab	95 ab	95 ab	99 a
18.6	98 a	98 a	98 a	99 a	99 a
22	98 a	98 a	98 a	98 a	99 a
25.6	98 a	98 a	99 a	99 a	99 a
29.5	98 a	99 a	99 a	99 a	99 a

[a]Means followed by a common letter do not significantly differ at P = 0.05 using Tukey's honestly significant difference test.

[b]Reduction in grassy arrowhead biomass relative to the nontreated control of 1871 g. A separate Tukey's honestly significant difference test was used to analyze biomass at P = 0.05.

[c]Control was measured using a scale of 0 = no control and 100= complete plant death based on visual symptoms.

Table 2.5. Pickerelweed control when treated with florpyrauxifen at titrated rates at 14, 28, 42, and 56 DAT evaluation timings and biomass reduction at two different locations in 2018.[a]

	Pickerelweed control[c]				
Florpyrauxifen	14 DAT	28 DAT	42 DAT	56 DAT	Biomass[b]
g ai ha^{-1}	%				g
3.6	30 h	24 hi	22 hi	21 i	52 c
7.3	78 fg	74 g	74 g	80 efg	76 b
11	83 d-g	86 b-g	81 d-g	85 c-g	85 ab
14.3	84 d-g	89 a-f	89 a-f	89 a-f	86 ab
18.6	88 a-f	90 a-f	89 a-f	91 a-e	88 ab
22	93 a-e	98 a	98 a	99 a	99 a
25.6	94 a-d	98 a	98 a	97 ab	99 a
29.5	98 a	99 a	99 a	99 a	99 a

[a]Means followed by a common letter do not significantly differ at P = 0.05 using Tukey's honestly significant difference test.

[b]Reduction in pickerelweed fresh weight biomass relative to the nontreated control of 323 g. A separate Tukey's honestly significant difference test was used to analyze biomass data at P = 0.05.

[c]Control was measured using a scale of 0 = no control and 100= complete plant death based on visual symptoms.

florpyrauxifen at the same rates. Similarly, pickerelweed biomass was reduced by 85% when treated with florpyrauxifen at 11 g ha^{-1}. These data indicate the florpyrauxifen application rate should not be below 11 g ha^{-1} when targeting pickerelweed.

In conclusion, florpyrauxifen will be a useful tool to manage aquatic weeds commonly found infesting rice or crawfish production systems such as alligatorweed, ducksalad, grassy arrowhead, or pickerelweed. Similarly, Beets and Netherland (2018) reported the potential for florpyrauxifen use on other aquatic weeds such as crested floating heart [*Nymphoides cristata* (Roxb) Kuntze], dioecious or monecious hydrilla (*Hydrilla verticillata* L.f. Royle), and Eurasian watermilfoil (*Myriophyllum spicatum* L.). In addition, these data suggest control will be similar to the maximum labeled rate of florpyrauxifen at 29.5 g ha^{-1} when alligatorweed is treated at 18.6 g ha^{-1}, ducksalad or grassy arrowhead are treated at 11 g ha^{-1}, pickerelweed is treated at 14.3 g ha^{-1}, and cattail is treated at 22 g ha^{-1}. These reduced rates can be used to manage these weeds without reducing herbicide efficacy; thus, improving economic returns for rice or crawfish producers. However, creeping water primrose growth was only suppressed in this study when treated with florpyrauxifen applied at the highest rate, indicating florpyrauxifen should be avoided where creeping water primrose is present.

Chapter 3
Florpyrauxifen-benzyl Mixture Interactions with Graminicides Used in Rice Production

Introduction

Rice (*Oryza sativa* L.) is the world's largest food crop and a plays a significant role in the diet for approximately half of the world's population, providing 20% of the total calories consumed worldwide (Kubo and Purevdorj 2004). As with other cropping systems throughout the world, weed management strategies are necessary to maximize yield and economic returns for rice producers (Chauhan 2012; Rodenburg and Johnson 2009). In 2012, approximately 73% of farm land in the United States received a herbicide application (USDA 2012). Consequently, the threat of herbicide-resistant weeds has become a major issue for rice producers in the United States. Several examples of herbicide resistance have been documented in the United States, such as barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv] resistant to propanil (Carey et al. 1995), quinclorac (Malik et al 2010), and imazethapyr (Riar et al. 2013). Additionally, rice flatsedge (*Cyperus iria* L.) (Riar et al. 2015) and yellow nutsedge (*Cyperus esculentus* L.) (Tehranchian et al. 2015) resistance to ALS-inhibiting herbicides also presents a weed management issue for rice producers.

Barnyardgrass is a summer annual bunchgrass member of the Poaceae family that propagates through seed, can produce up to 39,000 seeds per plant, prefers sunny areas containing moist soil and high nitrogen content, and competes with rice for nutrients, water, and space (Bagavathiannan et al. 2012; Chin 2001). The physiological and morphological characteristics of barnyardgrass are more diverse than any other *Echinochloa* species, and can express many phenotypic differences such as plant height, seed size, panicle shape, and presence of awns (Barrett 1983; Smith 1988; Smith et al. 1977). Barnyardgrass has historically been one of the most troublesome weeds in rice production in the United States and can potentially remove 60 to 80% of available nitrogen from the soil (Holm et al. 1977; Noda et al. 1968; Smith 1968; 1974). A survey conducted in 2011 reports barnyardgrass is the most problematic weed in Arkansas and Mississippi rice production (Norsworthy et al. 2013).

Yellow nutsedge and rice flatsedge are members of the Cyperaceae family that can tolerate high soil moisture and are commonly occurring in rice cropping systems (Bendixen and Nandihalli 1987; Webster 2014). Yellow nutsedge is a perennial weed that produces little to no viable seed and utilizes tubers as a primary reproductive mechanism; however, rice flatsedge is an annual weed that does not produce tubers and relies on high seed production for reproduction (Galinato et al. 1999; Thullen and Keeley 1979). Cultivated rice is considered nonefficient C_3 plant; however, both yellow nutsedge and rice flatsedge are C_4 plants and can more efficiently utilize nutrients and light (Smith 1988). Therefore, these two weeds can negatively interfere with rice production.

Hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh] is a member of the Fabaceae family that can grow up to 4-m tall (Bryson and DeFelice 2009). Additional identification characteristics include alternate pinnately compound leaves with opposite leaflets, 2- to 6-inflorescences on racemes borne in leaf axils, yellow petals up to 1.5 cm long, beak shaped or curved leguminous fruits up to 20 cm long, and brown seeds that are 2 times longer than wide. Hemp sesbania has been reported as the most competitive broadleaf weed encountered by rice and 12 plants m^{-2} can reduce rice yield by 50% (Smith 1988). In addition to yield reductions, the presence of hemp sesbania seeds in harvested rice grain negatively impact the value of the harvested crop.

Similar to hemp sesbania, Indian jointvetch (*Aeschynomene indica* L.) is a common weed interfering with rice production (Webster 2014). This member of the Fabaceae family can grow to 2.5 m tall and is identified by evenly pinnately compound leaves, sensitive leaflets that fold when touched, lance-shaped stipules, inflorescences up to 10 cm long subtended by a toothed bract, and kidney-shaped seeds (Bryson and DeFelice 2009). Smith (1988) reported northern jointvetch (*A. virginica* L.), a close relative of Indian jointvetch, is the second most competitive broadleaf weed in rice and it has been reported that 29 plants m^{-2} reduced rice yields 50%.

The utilization of herbicides with alternative modes of action would serve as an additional component to an overall weed resistance management program (Norsworthy et al. 2012). Florpyrauxifen-benzyl (florpyrauxifen) was released for commercial use in 2018 and represents a new structural class of synthetic auxin herbicides in the arylpicolinate family. Unlike other synthetic auxin herbicides, florpyrauxifen exhibits strong binding affinity for auxin signaling F-box proteins with preference for the AFB5-Auxin co-receptor protein, instead of favoring TIR1 protein; therefore, signifying a unique site of action (Bell et al. 2015; Epp et al. 2016; Jeschke 2015b). In addition, florpyrauxifen must be metabolically converted to its active acid form in weeds through enzymatic hydrolysis; therefore, increased soil moisture conditions play a significant role in the conversion of this herbicide to its active form (Jeschke 2015a; Epp et al. 2016; Miller and Norsworthy 2018b).

Florpyrauxifen exhibits broad spectrum activity on broadleaf, grass, and sedge weeds (Miller and Norsworthy 2018a; Telo et al. 2018). Auxin-mimicing herbicides like 2,4-D are typically known for broadleaf weed activity and have been used since the 1940s with little to no grass or sedge activity (Grossman 2010). Similarly, dicamba is used to manage broadleaf weeds in corn, cotton, and soybean (Shaner 2014). Quinclorac has activity on broadleaf and grass weeds in rice and turfgrass; however, quinclorac has little to no *Cyperus* species activity and barnyardgrass resistance can be problematic (Malik et al. 2010; Shaner 2014).

The economic value of applying herbicides in mixtures is well documented (Carlson et al. 2011; Pellerin et al. 2003; Pellerin and Webster 2004; Webster et al. 2012). Weed response to herbicides applied in a mixture will result in one of three interactions: synergistic, antagonistic, or neutral (Berenbaum 1981; Blouin et al. 2010; Fish et al. 2015, 2016; Hatzios and Penner 1985; Morse 1978; Nash 1981; Rustom et al. 2018, 2019; Streibig et al. 1998). Herbicide antagonism is defined by Beste (1983) as "an interaction of two or more chemicals such that the effect when combined is less than the predicted effect based on each chemical applied separately." Synergism is the inverse of antagonism, where the effect when combined exceeds the predicted effect based on the herbicides applied separately. A neutral or additive response is indicated by similar effects when herbicides are applied combined or alone.

Group 1 herbicides are commonly known as graminicides and inhibit acetyl coenzyme A carboxylase (ACCase), the enzyme responsible for catalyzing the first step in fatty acid synthesis for cell membrane production (Burton et al. 1989; Focke and Lichtenthaler 1987; Herbert et al. 1997). ACCase herbicides are typically used for grass management and have little to no activity on broadleaf weeds due to different types of ACCase enzyme present in each species (Rendina and Felts 1988; Secor and Cseke 1988). There are currently three different ACCase herbicides labeled for use in rice in the United States: cyhalofop-butyl (cyhalofop), fenoxaprop-p-ethyl (fenoxaprop), and quizalofop-p-ethyl (quizalofop) (Camacho et al. 2019; Shaner 2014). Quizalofop can only be used in Provisia® rice, a quizalofop-resistant cultivar released for commercial use in 2018 (Camacho et al. 2020).

ACCase herbicide activity is often antagonized when mixed with broadleaf and/or sedge herbicides (Barnwell and Cobb 1994). Quizalofop activity is reported to be antagonized for weedy rice (*O. sativa* L.) and barnyardgrass control when mixed with synthetic auxin herbicides such as 2,4-D, triclopyr, or quinclorac (Webster et al. 2019). Additionally, quizalofop activity can be antagonized by ALS-inhibiting herbicides such as penoxsulam or bispyribac (Rustom et al. 2018), and contact herbicides such as propanil (Rustom et al. 2019). Scherder et al. (2005) observed cyhalofop-butyl antagonism for activity on barnyardgrass and broadleaf signalgrass (*Urochloa platyphylla* Munro ex. C. Wright) when the herbicide was applied mixed with with halosulfuron, triclopyr, or propanil. Zhang et al. (2005) observed antagonism of fenoxaprop activity on barnyardgrass when applied in a mixture with bensulfuron, carfentrazone, halosulfuron, or triclopyr.

When analyzing mixture interactions statistically, antagonstic, synergistic, or neutral/additive responses are typically determined by using the Colby (1967) procedure. This procedure calculates an expected response for mixtures based on the activity of each herbicide applied alone, to be compared with the observed response of the herbicides applied together. Blouin et al. (2004) suggests if the expected response is defined as a nonlinear function of the means for the herbicides when applied alone, then standard linear model methodology for tests of hypotheses does not apply. Thus, the Blouin et al. (2004) nonlinear mixed-model is more sensitive than Colby’s linear model in detecting significant differences in herbicide response. Blouin et al. (2010) further modified the nonlinear model into the augmented mixed-model, which proved to be more versatile than the Blouin et al. (2004) nonlinear mixed model when observing fenoxaprop mixtures with various rice herbicides.

Florpyrauxifen will provide an additional tool for producers to control a broad spectrum of weeds in rice production. Smith (1968) suggests grass weeds are the most competitive weeds with rice. ACCase herbicides are effective for grass management in rice production; however, given the history of ACCase herbicide antagonism by other herbicides, research must be conducted to understand the impact florpyrauxifen has when applied in a mixture with these herbicides. These responses will aid in developing weed control strategies for producers choosing to utilize this new technology. The overall objective of this research was to determine antagonistic, synergistic, or neutral interactions of cyhalofop, quizalofop, or fenoxaprop applied in a mixture with florpyrauxifen.

Materials and Methods

A study was conducted in 2017 and 2018 at the H. Rouse Caffey Rice Research Station (RRS) near Crowley, Louisiana to evaluate cyhalofop, fenoxaprop, and quizalofop activity when applied independently or in a mixture with florpyrauxifen. The soil type at the RRS is a Crowley silt loam (fine smectic, thermic Typic Albaqualfs) with a pH of 6.4 and 1.4% organic matter. Field preparation consisted of a fall and spring disking followed by (FB) two passes in opposite directions with a two-way bed conditioner consisting of rolling baskets and S-tine harrows set at 6 cm depth.

Plot size was 1.5- by 5.2-m with eight-19.5cm drill-seeded rows planted with ‘PVL01’ rice, an ACCase-herbicide resistant long grain rice, at a rate of 67 kg ha^{-1}. The research area was naturally infested with barnyardgrass at 100- to 200-plants m^{-2} at 2- to 8-cm tall with 1- to 4-leaves, yellow nutsedge at 10- to 20-plants m^{-2} at 8- to 20-cm tall with 3- to 9-leaves , rice flatsedge at 60- to 150-plants m^{-2} at 3- to 9-cm tall with 3- to 6-leaves , hemp sesbania at 10- to 20-plants m^{-2} at 5- to 10-cm tall with 1- to 2-leaves, and Indian jointvetch at 10- to 30-plants m^{-2}

at 5- to 8-cm tall with 1- to 3-leaves. The area was surface irrigated to a depth of 2.5 cm 24 hours after planting. A permanent 10-cm flood was established when the rice reached the five-leaf to one-tiller stage, and was maintained until two weeks prior to harvest.

Visual evaluations for this study included crop injury, barnyardgrass, yellow nutsedge, rice flatsedge, hemp sesbania, and Indian jointvetch control expressed as a percent with 0 = no injury or control and 100 = complete plant death at 14, 28, and 42 DAT. PVL01 rice plant height was recorded from four plants in each plot measured from the ground to the tip of the extended panicle (data not shown). The center four rows of rice were harvested with a Mitsubishi VM3 (Mitsubishi Corporation, 3-1, Marunouchi 2- chome, Chiyoda-ky, Tokyo, Japan) plot combine and grain yield was adjusted to 12% moisture.

The study was a randomized complete block design with a factorial arrangement of treatments with four replications. Factor A was florpyrauxifen applied at 29 g ai ha^{-1} or no florpyrauxifen (Table 3.1). Factor B was cyhalofop applied at 314 g ai ha^{-1}, fenoxaprop applied at 66 g ai ha^{-1}, quizalofop applied at 120 g ai ha^{-1}, or no mixture herbicide (Table 3.1). The entire research area received an application of halosulfuron at 53 g ai ha^{-1} 42 days after the initial mixture treatment (DAT) for maintenance of broadleaf and sedge weeds when the rice was at the panicle initiation growth stage to aid rice harvest. A methylated seed oil (MSO; Leci-Tech, Loveland Products, Loveland, CO) was added to each herbicide application at a rate of 1% v/v. Each herbicide application was applied when the rice was at the 3- to 4-leaf growth stage with a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} with five flat-fan 110015 nozzles spaced at 35 cm.

Control data collected were analyzed using the Blouin et al. (2010) augmented mixed model to determine synergistic, antagonistic, or neutral responses for herbicide mixtures by comparing an expected control calculated based on activity of each herbicide applied alone to an observed control. Rough rice yield data were analyzed using the MIXED procedure in SAS (release 9.4 SAS Institute, Cary, NC). The fixed effects for all models were the herbicide treatments and evaluation timing. The random effects were years, replication within years, and plots. Considering year or combination of years as a random effect accounts for different environmental conditions each year having an effect on herbicide treatments for that year (Carmer et al. 1989; Hager et al. 2003). Normality of effects over all DAT was checked with the use of the UNIVARIATE procedure of SAS and significant normality problems were not observed.

Table 3.1. Herbicide information for all products used in the study[a]

Herbicide common name	Herbicide trade name	Rate g ai ha^{-1}	Manufacturer
Cyhalofop-butyl	Clincher	314	Corteva Agriscience, Indianapolis, IN
Fenoxaprop-p-ethyl	Ricestar	66	Gowan Company, Yuma, AZ
Florpyrauxifen-benzyl	Loyant	29	Corteva Agriscience, Indianapolis, IN
Quizalofop-p-ethyl	Provisia	120	BASF Corporation, Research Triangle Park, NC

[a]All treatments were applied with methylated seed oil (MSO; Leci-Tech, Loveland Products, Loveland, CO) 1% v/v.

Results and Discussion

An antagonistic response for barnyardgrass control occurred at 14 DAT when florpyrauxifen was applied in a mixture with fenoxaprop (Table 3.2). The expected control of 93% was reduced to an observed control of 81%. However, barnyardgrass treated with all other mixtures indicated a neutral response at 14 DAT. At 28 DAT, neutral responses were observed for all mixtures, indicating the initial antagonism observed when florpyrauxifen was mixed with fenoxaprop was overcome. Similarly, research conducted by Zhang et al. (2005) reported fenoxaprop activity on barnyardgrass was antagonized by triclopyr at 20 DAT; however, the initial antagonism was overcome by 30 DAT. A similar neutral response was observed at 42 DAT for barnyardgrass treated with all mixtures. These data contradict Webster et al. (2019) reports of barnyardgrass antagonism when treated with quizalofop applied mixed with auxin herbicides such as 2,4-D, triclopyr, and quinclorac. Barnwell and Cobb (1994) suggested one or more of the processes involved in early auxin action is the basis for ACCase antagonism by auxin herbicides; therefore, the unique binding affinity exhibited by florpyrauxifen-benzyl in weeds could explain this contradiction.

Table 3.2. Barnyardgrass control with florpyrauxifen applied alone or mixed with graminicides labeled for use in rice production using Blouin's modified Colby's analysis in 2017 and 2018.

		Florpyrauxifen-benzyl (g ai ha^{-1})			
		0	29		
Mixture Herbicide[a]	Rate	Observed	Expected	Observed[b]	P value[c]
	g ai ha^{-1}	% of control			
14 DAT[d]					
None	—	0	—	77	—
Cyhalofop-butyl	314	61	91	84	0.1249
Fenoxaprop-p-ethyl	66	70	93	81-	0.0144
Quizalofop-p-ethyl	120	90	95	98	0.5906
28 DAT					
None	—	0	—	86	—
Cyhalofop-butyl	314	76	97	89	0.1374
Fenoxaprop-p-ethyl	66	64	95	89	0.2192
Quizalofop-p-ethyl	120	99	99	98	0.7701
42 DAT					
None	—	0	—	83	—
Cyhalofop-butyl	314	54	92	84	0.0672
Fenoxaprop-p-ethyl	66	51	91	87	0.3135
Quizalofop-p-ethyl	120	99	99	98	0.7540

[a]Evaluation dates for each respective herbicide mixture

[b]Observed means followed with a minus (-) sign are significantly different from Blouin's modified Colby's expected responses at the 5% level, indicating an antagonistic response. No (–) sign indicates a neutral response.

[c]$P < 0.05$ indicates an antagonistic response, $P > 0.05$ indicates a neutral response

[d]DAT, days after treatment

A synergistic response was observed for yellow nutsedge control at 14 DAT when florpyrauxifen was applied in a mixture with quizalofop (Table 3.3). Expected control for this treatment calculated using Blouin's modified Colby's analysis was 88%; however, observed control was increased to 98%. Similarly, Lollar (2010) reports synergistic interactions when yellow nutsedge was treated with a mixture of halosulfuron and diazinon. At 28 and 42 DAT, yellow nutsedge treated with all florpyrauxifen plus graminicide mixtures was greater than 97%, compared with an expected control of 98%, indicating a neutral response. These data are similar to Miller and Norsworthy (2018a) reports of a neutral response when yellow nutsedge was treated with florpyrauxifen plus cyhalofop.

Table 3.3. Yellow nutsedge control with florpyrauxifen applied alone or mixed with graminicides labeled for use in rice production using Blouin's modified Colby's analysis in 2017 and 2018.

		Florpyrauxifen-benzyl (g ai ha^{-1})			
		0	29		
Mixture Herbicide[a]	Rate	Observed	Expected	Observed[b]	P value[c]
	g ai ha^{-1}	% of control			
14 DAT[d]					
None	—	0	—	88	—
Cyhalofop-butyl	314	0	88	88	0.6855
Fenoxaprop-p-ethyl	66	0	88	87	0.5437
Quizalofop-p-ethyl	120	0	88	97+	0.0000
28 DAT					
None	—	0	—	98	—
Cyhalofop-butyl	314	0	98	98	0.8385
Fenoxaprop-p-ethyl	66	0	98	98	0.9188
Quizalofop-p-ethyl	120	0	98	97	0.3088
42 DAT					
None	—	0	—	98	—
Cyhalofop-butyl	314	0	98	98	1.0000
Fenoxaprop-p-ethyl	66	0	98	98	1.0000
Quizalofop-p-ethyl	120	0	98	98	0.6104

[a]Evaluation dates for each respective herbicide mixture

[b]Observed means followed with a plus (+) sign are significantly different from Blouin's modified Colby's expected responses at the 5% level, indicating a synergistic response. Means

Table 3.3 cont'd
followed by a minus (-) sign indicate an antagonistic response. No + or – sign indicates a neutral response.
[c]P < 0.05 indicates a synergistic response, P > 0.05 indicates a neutral response
[d]DAT, days after treatment

At 14 DAT, a synergistic response was observed for rice flatsedge control when treated with florpyrauxifen mixed with quizalofop (Table 3.4). The expected control was 94%, compared with an observed control of 98%. However, an antagonistic response was observed 14 DAT when florpyrauxifen was mixed with fenoxaprop with an expected control of 94% reduced to an observed control of 88%. By 28 DAT, the initial antagonism observed was overcome, resulting in a neutral response. Similar to yellow nutsedge control at 28 and 42 DAT, observed rice flatsedge control for each mixture was above 98%, compared with an expected control of 99% at each evaluation date, indicating a neutral response. These data suggest florpyrauxifen can be mixed with ACCase herbicides for yellow nutsedge or rice flatsedge control.

Table 3.4. Rice flatsedge control with florpyrauxifen applied alone or mixed with graminicides labeled for use in rice production using Blouin's modified Colby's analysis in 2017 and 2018.

		Florpyrauxifen-benzyl (g ai ha^{-1})			
		0	29		
Mixture Herbicide[a]	Rate	Observed	Expected	Observed[b]	P value[c]
	g ai ha^{-1}	% of control			
14 DAT[d]					
None	—	0	—	94	—
Cyhalofop-butyl	314	0	94	92	0.2244
Fenoxaprop-p-ethyl	66	0	94	88-	0.0001
Quizalofop-p-ethyl	120	0	94	98+	0.0001
28 DAT					
None	—	0	—	99	—
Cyhalofop-butyl	314	0	99	98	0.5421
Fenoxaprop-p-ethyl	66	0	99	98	0.6257
Quizalofop-p-ethyl	120	0	99	99	0.9029
42 DAT					
None	—	0	—	99	—

Table 3.4 cont'd

Table 3.4 cont'd

		Florpyrauxifen-benzyl (g ai ha^{-1})			
		0	29		
Mixture Herbicide[a]	Rate	Observed	Expected	Observed[b]	P value[c]
	g ai ha^{-1}	——— % of control ———			
Cyhalofop-butyl	314	0	99	98	0.8072
Fenoxaprop-p-ethyl	66	0	99	98	0.6257
Quizalofop-p-ethyl	120	0	99	98	0.3936

[a]Evaluation dates for each respective herbicide mixture

[b]Observed means followed with a plus (+) sign are significantly different from Blouin's modified Colby's expected responses at the 5% level, indicating a synergistic response. Means followed by a minus (-) sign indicate an antagonistic response. No + or – sign indicates a neutral response.

[c]P < 0.05 indicates a synergistic or antagonistic response, P > 0.05 indicates a neutral response

[d]DAT, days after treatment

Control of Indian jointvetch (Table 3.5) and hemp sesbania (data not shown) were similar. Neutral responses were observed for each florpyrauxifen mixture throughout the study and neither observed or expected control was below 98%. These data are similar to Miller and Norsworthy (2018a) reporting no antagonistic interactions indicated by hemp sesbania treated with florpyrauxifen mixed with contact or systemic herbicides.

Crop injury was less than 10% across all evaluations (data not shown). PVL01 rough rice yield was 3350 kg ha^{-1} when treated with florpyrauxifen alone. Rough rice yield was decreased to 2460 to 2470 kg ha^{-1} when cyhalofop and fenoxaprop were applied alone, and these decreases are likely due to decreased activity on barnyardgrass (Table 3.6) and no activity on broadleaf or sedge weeds before halosulfuron was applied to all treatments at 42 DAT. However, yield was increased to 4580 to 5040 kg ha^{-1} when florpyrauxifen was applied in a mixture with cyhalofop, fenoxaprop, or quizalofop. These yield increases can be attributed to increased weed control when florpyrauxifen was applied in a mixture with cyhalofop, fenoxaprop, or quizalofop, compared with each of the herbicides applied alone. Although activity on barnyardgrass was initially antagonized when florpyrauxifen was applied mixed with fenoxaprop, the antagonism was overcome and had no effect on rough rice yield.

Table 3.5. Indian jointvetch control with florpyrauxifen applied alone or mixed with graminicides labeled for use in rice production using Blouin's modified Colby's analysis in 2017 and 2018.

		Florpyrauxifen-benzyl (g ai ha^{-1})			
		0	29		
Mixture Herbicide[a]	Rate	Observed	Expected	Observed[b]	P value[c]
	g ai ha^{-1}	— % of control —			
14 DAT[d]					
None	—	0	—	98	—
Cyhalofop-butyl	314	0	98	97	0.1067
Fenoxaprop-p-ethyl	66	0	98	97	0.2252
Quizalofop-p-ethyl	120	0	98	98	0.1067
28 DAT					
None	—	0	—	98	—
Cyhalofop-butyl	314	0	98	98	0.6851
Fenoxaprop-p-ethyl	66	0	98	98	0.4179
Quizalofop-p-ethyl	120	0	98	99	0.1067
42 DAT					
None	—	0	—	99	—
Cyhalofop-butyl	314	0	98	98	0.6851
Fenoxaprop-p-ethyl	66	0	98	99	0.4178
Quizalofop-p-ethyl	120	0	98	99	0.2251

[a]Evaluation dates for each respective herbicide mixture

[b]Observed means followed with a plus (+) sign are significantly different from Blouin's modified Colby's expected responses at the 5% level, indicating a synergistic response. Means followed by a minus (-) sign indicate an antagonistic response. No + or – sign indicates a neutral response.

[c]$P < 0.05$ indicates a synergistic response, $P > 0.05$ indicates a neutral response

[d]DAT, days after treatment

In conclusion, it is important to understand the interactions of florpyrauxifen when mixed with other herbicides before developing weed management programs to utilize this new technology. Similar to research conducted by Miller and Norsworthy (2018b), these data suggest applying florpyrauxifen in a mixture with cyhalofop, fenoxaprop, and quizalofop can broaden the

Table 3.6. Rough rice yields of 'PVL01' rice treated with florpyrauxifen and each respective mixture in 2017 and 2018.

Mixture herbicide[a]	Rate	Florpyrauxifen-benzyl (g ai ha^{-1}) 0	120
	g ai ha^{-1}	kg ha^{-1}	
None	—	0 d	3350 b
Cyhalofop-butyl	314	2460 c	4640 a
Fenoxaprop-p-ethyl	66	2370 c	4580 a
Quizalofop-p-ethyl	120	3080 bc	5040 a

[a]Respective herbicide mixtures

[b]Means followed by a common letter are not significantly different at P = 0.05 with the use of Tukey's HSD

weed control spectrum to increase PVL01 rice yields with little to no antagonistic interactions occurring for barnyardgrass, yellow nutsedge, rice flatsedge, Indian jointvetch, or hemp sesbania control. However, these data contradict Scott (2002) reports of cyhalofop antagonism by auxin herbicides such as 2,4-D for barnyardgrass control. Initial antagonism of barnyardgrass and rice flatsedge activity when florpyrauxifen was applied mixed with fenoxaprop was overcome and had little to no impact on rough rice yield. Rustom et al. (2018) similarly observed initial barnyardgrass antagonism being overcome; however, yield data indicated initially antagonized weeds competed with rice causing rough rice yield reductions. Although auxin herbicides have a history of antagonizing ACCase herbicide activity on barnyardgrass in rice production, these data highlight the flexibility of mixing florpyrauxifen with ACCase-inhibiting herbicides, which can be beneficial for producers in the United States.

Chapter 4
Florpyrauxifen-benzyl Mixture Interactions with ALS-inhibiting Herbicides Used in Rice Production

Introduction

Rice (*Oryza sativa* L.) was domesticated between 8000 and 10000 years ago and has since become the world's largest food crop (Greenland 1997; Sweeney and McCouch 2007), and a majority of the rice produced in the United States is produced in Arkansas, California, Louisiana, Mississippi, Texas, and Missouri (USDA NASS 2020). In 2019, rice was planted on approximately 172,000 hectares in Louisiana, the third largest rice producing state in the country. Successful weed management strategies have proven to be essential to maximize yield and economic returns, and are often the driving force for rice production systems in Louisiana (Carlson et al. 2011; Chauhan 2012; Rodenburg and Johnson 2009).

Herbicides are the foundation for weed control in the United States (Smith and Hill 1990). Almost every rice hectare in the United States receives an annual herbicide application and most receive multiple applications (Gianessi and Reigner 2007). Consequently, several examples of herbicide-resistant weeds have been documented in rice production such as barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv] resistant to propanil (Carey et al. 1995), quinclorac (Malik et al. 2010), and imazethapyr (Riar et al. 2013). Additionally, rice flatsedge (*Cyperus iria* L.) (Tehranchian et al. 2015) and yellow nutsedge (*Cyperus esculentus* L.) (Riar et al. 2015) resistance to ALS-inhibiting herbicides also presents a weed management issue for rice producers.

Barnyardgrass has been reported as one of the most troublesome weeds in United States rice production (Holm et al. 1977; Noda et al. 1968; Norsworthy et al. 2013; Smith 1968; Smith 1974). Barnyardgrass is a summer annual bunchgrass member of the Poaceae family that is well adapted for growth in sunny areas with moist soil and high nitrogen content (Bagavathiannan et al. 2012; Chin 2001). Barnyardgrass biotypes can have different phenotypic characteristics such as expression of awns, differences in height, and size or shape of seeds and panicles (Barrett 1983; Smith 1988; Smith et al. 1977). Barnyardgrass prefers moist, disturbed soil for germination; however, some biotypes have adapted to germinate under water (Smith 1988).

Yellow nutsedge and rice flatsedge are members of the Cyperaceae family that commonly infest rice cropping systems (Bendixen and Namdihalli 1987; Webster 2014). Yellow nutsedge is a perennial weed that primarily reproduces by tubers that has little to no viable seed; however, rice flatsedge is an annual weed that reproduces and spreads primarily through seed production (Galinato et al. 1999; Thullen and Keeley 1979). Both yellow nutsedge and rice flatsedge are C_4 plants and can more efficiently utilize nutrients and light than a cultivated C_3 plant such as rice (Smith 1988). Therefore, these two weeds can be major weeds for rice producers.

Hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh] is a summer annual member of the Fabaceae family that can grow up to 4-m tall (Bryson and DeFelice 2009). Additional botanical characteristics include alternate pinnately compound leaves with opposite leaflets, 2- to 6-inflorescences on racemes borne in leaf axils, yellow petals up to 1.5-cm long, beak shaped or curved leguminous fruits up to 20-cm long, and brown seeds that are 2 times longer than wide. Smith (1988) suggested hemp sesbania is the most competitive broadleaf weed encountered by rice, and 12 plants m^{-2} can reduce rice yield up to 50%. In addition to yield reductions, the presence of hemp sesbania seeds in harvested rice grain negatively impact the value of the harvested crop.

Indian jointvetch (*Aeschynomene* indica L.) is another summer annual weed in the Fabaceae family that interferes with rice production in Louisiana (Webster 2014). Indian jointvetch can grow to 2.5-m tall and is identified by evenly pinnately compound leaves, sensitive leaflets that fold when touched, lance-shaped stipules, inflorescences up to 10-cm long subtended by a toothed bract, and kidney-shaped seeds (Bryson and DeFelice 2009). Smith (1988) reported northern jointvetch (*Aeschynomene virginica* L.), a close relative to Indian jointvetch, is the second most competitive broadleaf weed in rice, and 29 plants m^{-2} can reduce rice yields up to 50%.

Floypyrauxifen-benzyl (florpyrauxifen) is an auxin-mimicing herbicide in the arylpicolinate family labeled for use in rice production in 2018 with activity on broadleaf, grass, and sedge weeds. In order to become active in the plant, florpyrauxifen must be converted to florpyrauxifen-acid through enzymatic hydrolysis; therefore, soil moisture conditions can have a significant impact on florpyrauxifen uptake, conversion of the herbicide to the active form, and ultimately the activity of the compound on target weeds (Epp et al. 2016; Jeschke 2015a; Miller and Norsworthy 2018b). Florpyrauxifen has unique binding affinity to a different protein than typical auxin herbicides; therefore, the unique binding characteristics to different proteins represents a new mechanism of action for use in rice production (Bell et al. 2015; Epp et al. 2016; Jeschke 2015b). Other auxin herbicides such as 2,4-D and dicamba are typically used for broadleaf weed management with little to no activity on grasses or sedges (Grossman 2010; Shaner 2014). Quinclorac is an auxin herbicide labeled for use in rice production with broadleaf and grass activity; however, quinclorac has little to no sedge activity and barnyardgrass resistance has been documented (Malik et al. 2010; Shaner 2014).

Herbicides are commonly applied in mixtures to improve activity, broaden the weed control spectrum, and maximize economic returns by saving money and time (Carlson et al. 2011; Pellerin et al. 2003; Pellerin and Webster 2004; Webster et al. 2012). Herbicides applied in mixtures tend to have different modes of action, and these mixtures will result in one of three weed responses: synergistic, antagonistic, or neutral (Berenbaum 1981; Blouin 2010; Fish et al. 2015, 2016; Hatzios and Penner 1985; Morse 1978; Nash 1981; Rustom et al. 2018, 2019; Streibig et al. 1998). Herbicide antagonism is defined by Beste (1983) as “an interaction of two or more chemicals such that the effect when combined is less than the predicted effect based on each chemical applied separately”. Synergism is the inverse of antagonism, where the effect when combined exceeds the predicted effect based on the herbicides applied separately. A neutral response is indicated by similar effects when herbicides are applied in a mixture or alone.

Herbicides used for grass control in rice production have a history of antagonism when applied in a mixture with other herbicides (Rustom et al. 2018; 2019; Scherder et al. 2005; Scott 2002; Webster et al. 2019; Zhang et al. 2005). Antagonism of quizalofop activity by Acetolactate synthase-inhibiting (ALS) (Rustom et al. 2018), contact (Rustom et al. 2019), and auxin (Webster et al. 2019) herbicides on barnyardgrass has been reported. Zhang et al. (2005) suggested fenoxaprop-p-ethyl activity on barnyardgrass can be antagonized by carfentrazone, halosulfuron, bensulfuron, and triclopyr. Additional antagonism of barnyardgrass activity has been reported by Fish et al. (2015) when imazethapyr was mixed with propanil plus thiobencarb.

Colby’s (1967) method is a linear statistical model typically used to determine a synergistic, antagonistic, or additive/neutral response for herbicide mixtures. Colby’s procedure calculates an expected response based on the activity of herbicides applied alone and comparing the expected response with an observed response. Blouin et al. (2004) suggests if the expected response is defined as nonlinear function of the means for the herbicides when applied alone, then the standard linear model methodology for tests of hypotheses does not apply; thus, the Blouin et al. (2004) nonlinear mixed-model is more sensitive than Colby's linear model in detecting significant differences in herbicide response. Blouin et al. (2010) further modified the nonlinear model into an augmented mixed-model, which proved to be more sensitive than the Blouin et al. (2004) nonlinear mixed model when observing fenoxaprop-p-ethyl mixtures with various rice herbicides.

Florpyrauxifen represents a new herbicide mechanism of action for use in rice production and is a beneficial tool for producers to control a broad spectrum of weeds in Louisiana. However, given the history of ACCase herbicide antagonism, research to understand mixture interactions of florpyrauxifen with other herbicides is necessary before implementing this new herbicide in a weed management program. Weed responses to herbicide mixtures will aid in developing weed control strategies for producers choosing to use this new technology and rotate herbicide modes of action. The overall objective of this research is to evaluate the impact of ALS herbicides on florpyrauxifen activity.

Materials and Methods

A field study was conducted in 2017 and 2018 at the H. Rouse Caffey Rice Research Station (RRS) near Crowley, Louisiana to evaluate the activity of florpyrauxifen and ALS-inhibiting herbicides when applied independently or in a mixture. The soil type at the RRS is a Crowley silt loam (fine smectic, thermic Typic Albaqualfs) with a pH of 6.4 and 1.4% organic matter. Field preparation consisted of a fall and spring disking followed by two passes in opposite directions with a two-way bed conditioner consisting of rolling baskets and S-tine harrows set at 6 cm depth.

Plot size was 1.5- by 5.2-m with eight-19.5 cm drill-seeded rows planted with 'PVL01', an ACCase-herbicide resistant long grain rice, at a rate of 67 kg ha^{-1}. The research area was naturally infested with barnyardgrass at 100- to 200-plants m^{-2} at 2- to 8-cm tall with 1- to 4-leaves, yellow nutsedge at 10- to 20-plants m^{-2} at 8- to 20-cm tall with 3- to 9-leaves, rice flatsedge at 60- to 150-plants m^{-2} at 3- to 9-cm tall with 3- to 6-leaves, hemp sesbania at 10- to 20-plants m^{-2} at 5- to 10-cm tall with 1- to 2-leaves, and Indian jointvetch at 10- to 30-plants m^{-2} at 5- to 8-cm tall with 1- to 3-leaves. The area was surface irrigated to a depth of 2.5 cm 24-hours after planting. A permanent 10-cm flood was established when the rice reached the five-leaf to one-tiller stage, and was maintained until two weeks prior to harvest.

Visual evaluations for this study included crop injury and barnyardgrass, yellow nutsedge, rice flatsedge, hemp sesbania, and Indian jointvetch control expressed as a percent with 0 = no injury or control and 100 = complete plant death at 14, 28, and 42 DAT. PVL01 rice plant height was recorded from four plants in each plot measured from the ground to the tip of the extended panicle (data not shown). The center four rows of rice were harvested with a Mitsubishi VM3 (Mitsubishi Corporation, 3-1, Marunouchi 2- chome, Chiyoda-ky, Tokyo, Japan) plot combine and grain yield was adjusted to 12% moisture.

The study was a randomized complete block design with a factorial arrangement of treatments with four replications. Factor A was florpyrauxifen applied at 29 g ai ha^{-1} or no florpyrauxifen (Table 4.1). Factor B was bensulfuron applied at 43 g ai ha^{-1}, bispyribac applied at 34 g ai ha^{-1}, halosulfuron applied at 53 g ai ha^{-1}, imazosulfuron at 212 g ai ha^{-1}, orthosulfamuron at 74 g ai ha^{-1}, orthosulfamuron plus quinclorac at 491 g ai ha^{-1}, penoxsulam at 40 g ai ha^{-1} or no mixture herbicide (Table 4.1). A methylated seed oil (MSO) was added to each herbicide application at a rate of 1169 ml ha^{-1}. Each herbicide application was applied when the rice was at the three- to four-leaf growth stage with a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} with five flat-fan 110015 nozzles spaced at 35 cm.

Control data collected were analyzed using the Blouin et al. (2010) augmented mixed model to determine synergistic, antagonistic, or neutral responses for herbicide mixtures by comparing an expected control calculated based on activity of each herbicide applied alone to an observed control. Rough rice yield data were analyzed using the MIXED procedure in SAS (release 9.4 SAS Institute, Cary, NC). The fixed effects for all models were the herbicide treatments and evaluation timing. The random effects were years, replication within years, and plots. Considering year or combination of years as a random effect accounts for different environmental conditions each year having an effect on herbicide treatments for that year (Carmer et al. 1989; Hager et al. 2003). Normality of effects over all DAT was checked with the use of the UNIVARIATE procedure of SAS and normality problems were not observed.

Table 4.1. Herbicide information for all products used in experiment[a]

Herbicide common name	Herbicide trade name	Rate g ai ha^{-1}	Manufacturer
Bensulfuron	Londax	43	UPL North America Inc., King of Prussia, PA
Bispyribac	Regiment	34	Valent USA Corporation, Walnut Creek, CA
Florpyrauxifen-benzyl	Loyant	29	Corteva Agriscience, Indianapolis, IN
Halosulfuron	Permit	53	Gowan Company, Yuma, AZ
Imazosulfuron	League	212	Valent USA Corporation, Walnut Creek, CA
Orthosulfamuron	Strada	74	Nichino America Inc., Wilmington, DE
Orthosulfamuron + quinclorac	Strada XT	491	Nichino America Inc., Wilmington, DE
Penoxsulam	Grasp	40	Corteva Agriscience, Indianapolis, IN

[a]All treatments were applied with methylated seed oil (MSO; Leci-Tech, Loveland Products, Loveland, CO) at 1169 ml ha^{-1}.

Results and Discussion

An antagonistic interaction occurred for barnyardgrass treated with florpyrauxifen mixed with all of ALS-inhibiting herbicides evaluated at 14 DAT (Table 4.2). A severely antagonistic response was observed for barnyardgrass treated with florpyrauxifen mixed with orthosulfamuron when an expected control of 74% was reduced to 38%, with a P-value of 0.0001. In addition, the expected control for barnyardgrass treated with florpyrauxifen plus bensulfuron, halosulfuron, imazosulfuron, and orthosulfamuron plus quinclorac was 74%, compared with the observed control reduced to 59 to 61%.

The observed control for barnyardgrass treated with florpyrauxifen, bispyribac, and penoxsulam applied alone was 74, 73, and 58%, respectively, at 14 DAT. Although the observed control of florpyrauxifen applied in a mixture with bispyribac or penoxsulam was 81%, Blouin's (2010) modified Colby's suggests the expected control is 89 to 93%, based on the activity of each of the products applied alone. Therefore, the response is antagonistic. These data highlight the sensitivity of Blouin's (2010) modified Colby's procedure for detecting antagonistic herbicide interactions. Furthermore, these data contradict Miller and Norsworthy (2018a) reports of no antagonistic interactions by using Colby's (1967) method to analyze barnyardgrass treated with florpyrauxifen mixed with ALS-inhibiting herbicides.

Similar responses for barnyardgrass activity were observed at 28 DAT (Table 4.2). An antagonistic response for barnyardgrass activity was observed for all mixtures, except barnyardgrass treated with florpyrauxifen mixed with bensulfuron or imazosulfuron. The initial antagonistic response for these two mixtures at 14 DAT became neutral by 28 DAT, when the expected and observed control for barnyardgrass were similar at 72 and 73%, respectively. In comparison, the same expected control of 72% was reduced to an observed 44 to 59% control when barnyardgrass was treated with florpyrauxifen plus halosulfuron, orthosulfamuron, or orthosulfamuron plus quinclorac. These data indicate barnyardgrass activity for florpyrauxifen plus bensulfuron or imazosulfuron is similar to florpyrauxifen applied alone at 28 DAT; however, the initial activity on barnyardgrass for each mixture can be slowed.

At 42 DAT, similar neutral interactions for barnyardgrass control were observed when treated with florpyrauxifen plus bensulfuron or imazosulfuron (Table 4.2). Additionally, a neutral interaction occurred for barnyardgrass treated with florpyrauxifen applied in a mixture with penoxsulam. The expected control of 87% for this mixture compared with the observed control of 79%, with a P-value of 0.0520, approaching significance for antagonism. However, the antagonism observed for all other mixtures was not overcome, suggesting these mixtures should be avoided when barnyardgrass is present.

Table 4.2. Barnyardgrass control with florpyrauxifen applied alone or mixed with ALS-inhibiting herbicides labeled for use in rice production using Blouin's modified Colby's analysis in 2017 and 2018.

		Florpyrauxifen-benzyl (g ai ha^{-1})			
		0	29		
Mixture Herbicide[a]	Rate	Observed	Expected	Observed[b]	P value[c]
	g ai ha^{-1}	—	% of control	—	
14 DAT[d]					
None	—	0	—	74	—
Bensulfuron	43	0	74	61-	0.0019
Bispyribac	34	73	93	81-	0.0039
Halosulfuron	53	0	74	60-	0.0007
Imazosulfuron	212	0	74	62-	0.0077
Orthosulfamuron	74	0	74	38-	0.0001
Orthosulfamuron + quinclorac	491	0	74	59-	0.0002
Penoxsulam	40	58	89	81-	0.0349
28 DAT					
None	—	0	—	72	—

Table 4.2 cont'd

Table 4.2 cont'd

Mixture Herbicide[a]	Rate	Florpyrauxifen-benzyl (g ai ha^{-1}) 0 Observed	29 Expected	29 Observed[b]	P value[c]
	g ai ha^{-1}	% of control			
Bensulfuron	43	0	72	73	0.8818
Bispyribac	34	76	93	80-	0.0018
Halosulfuron	53	0	72	59-	0.0012
Imazosulfuron	212	0	72	72	0.9999
Orthosulfamuron	74	0	72	44-	0.0001
Orthosulfamuron + quinclorac	491	0	72	64-	0.0382
Penoxsulam	40	63	90	78-	0.0038
42 DAT					
None	—	0	—	72	—
Bensulfuron	43	0	72	69	0.4573
Bispyribac	34	71	92	78-	0.0006
Halosulfuron	53	0	72	62-	0.0120
Imazosulfuron	212	0	72	76	0.4573
Orthosulfamuron	74	0	72	42-	0.0001
Orthosulfamuron + quinclorac	491	0	72	63-	0.0265
Penoxsulam	40	52	87	79	0.0520

[a]Evaluation dates for each respective herbicide mixture
[b]Observed means followed by a minus (-) sign indicate an antagonistic response and are significantly different from Blouin's modified Colby's expected responses at the 5% level. Means response. No (–) sign indicates a neutral response.
[c]P < 0.05 indicated an antagonistic response, P > 0.05 indicates a neutral response
[d]DAT, days after treatment

An antagonistic interaction occurred for yellow nutsedge control at 14 DAT when florpyrauxifen was applied in a mixture with bensulfuron or orthosulfamuron-containing products (Table 4.3). Observed control for these mixtures was 84 to 87%, compared with an expected control of 96 to 97%. All other mixtures at 14 DAT indicated a neutral response for yellow nutsedge control. These data are similar to Miller and Norsworthy (2018a), who reported neutral interactions for yellow nutsedge activity when treated with florpyrauxifen mixed with halosulfuron or penoxsulam, indicating these two mixtures can be used for yellow nutsedge management; however, bensulfuron or orthosulfamuron mixtures with florpyrauxifen should be avoided.

By 28 DAT, the initial antagonism observed at 14 DAT was overcome, except when florpyrauxifen was applied in a mixture with orthosulfamuron (Table 4.3). Control for this treatment continued to be antagonistic, with an observed control of 89%, compared with an expected control of 98%. These data suggest orthosulfamuron should be avoided when considering mix partners for florpyrauxifen when yellow nutsedge is present. Similarly, York and Wilcut (1995) reported antagonistic interactions on yellow and purple nutsedge (*Cyperus rotundus* L.) when treated with bentazon, a contact herbicide, mixed with imazethapyr, an ALS-inhibiting herbicide.

However, by 42 DAT all mixtures evaluated resulted in a neutral response for yellow nutsedge control (Table 4.3). Observed control was above 91% for all treatments, compared with an expected control of 98 to 99%. These data indicate bispyribac, halosulfuron, imazosulfuron, and penoxsulam can be mixed with florpyrauxifen for yellow nutsedge management. Similar results have been reported when florpyrauxifen was applied in a mixture with several different ALS-inhibiting herbicides including halosulfuron, imazethapyr, and penoxsulam for yellow nutsedge control (Miller and Norsworthy 2018a).

Similar to barnyardgrass control at 14 DAT, an antagonistic interaction occurred for rice flatsedge control when florpyrauxifen was applied in a mixture with each ALS-inhibiting herbicide (Table 4.4). The expected control for these mixtures was 98 to 99%, compared with an observed control of 82 to 92%. These rice flatsedge data contradict Osterholt (2018), who reported neutral and synergistic interactions when rice flatsedge was treated with a prepackaged mixture of clomazone and pendimethalin mixed with various rates of propanil.

Table 4.3. Yellow nutsedge control with florpyrauxifen applied alone or mixed with ALS-inhibiting herbicides labeled for use in rice production using Blouin's modified Colby's analysis in 2017 and 2018.

		Florpyrauxifen-benzyl (g ai ha^{-1})			
		0	29		
Mixture Herbicide[a]	Rate	Observed	Expected	Observed[b]	P value[c]
	g ai ha^{-1}	——— % of control ———			
14 DAT[d]					
None	—	0	—	82	—
Bensulfuron	43	85	97	84-	0.0006
Bispyribac	34	88	98	94	0.2714
Halosulfuron	53	96	99	94	0.2370
Imazosulfuron	212	85	96	93	0.2531
Orthosulfamuron	74	79	96	86-	0.0035
Orthosulfamuron + quinclorac	491	83	97	87-	0.0071
Penoxsulam	40	87	98	96	0.6522
28 DAT					
None	—	0	—	86	—
Bensulfuron	43	88	98	96	0.5265
Bispyribac	34	91	99	99	0.9751
Halosulfuron	53	98	99	98	0.7284
Imazosulfuron	212	90	99	96	0.4719
Orthosulfamuron	74	82	98	89-	0.0309
Orthosulfamuron + quinclorac	491	87	98	93	0.1755
Penoxsulam	40	90	99	98	0.8690
42 DAT					
None	—	0	—	90	—
Bensulfuron	43	87	99	96	0.4551
Bispyribac	34	92	99	97	0.6974
Halosulfuron	53	98	99	98	0.7439
Imazosulfuron	212	89	99	96	0.4258
Orthosulfamuron	74	83	98	91	0.0533
Orthosulfamuron + quinclorac	491	84	98	91	0.0741
Penoxsulam	40	92	99	96	0.5235

[a]Evaluation dates for each respective herbicide mixture

[b]Observed means followed by a minus (-) sign indicate an antagonistic response and are significantly different from Blouin's modified Colby's expected responses at the 5% level. Means response. No (–) sign indicates a neutral response.

[c]$P < 0.05$ indicated an antagonistic response, $P > 0.05$ indicates a neutral response

[d]DAT, days after treatment

Table 4.4. Rice flatsedge control with florpyrauxifen applied alone or mixed with ALS-inhibiting herbicides labeled for use in rice production using Blouin's modified Colby's analysis in 2017 and 2018.

		Florpyrauxifen-benzyl (g ai ha^{-1})			
		0	29		
Mixture Herbicide[a]	Rate	Observed	Expected	Observed[b]	P value[c]
	g ai ha^{-1}	—— % of control ——			
14 DAT[d]					
None	—	0	—	87	—
Bensulfuron	43	87	98	82-	0.0000
Bispyribac	34	86	98	92-	0.0009
Halosulfuron	53	91	99	92-	0.0004
Imazosulfuron	212	88	98	92-	0.0003
Orthosulfamuron	74	88	98	86-	0.0000
Orthosulfamuron + quinclorac	491	88	98	91-	0.0002
Penoxsulam	40	84	98	92-	0.0013
28 DAT					
None	—		—	96	—
Bensulfuron	43	93	99	96	0.0742
Bispyribac	34	97	99	98	0.5472
Halosulfuron	53	98	99	98	0.4821
Imazosulfuron	212	89	99	97	0.1868
Orthosulfamuron	74	86	99	91-	0.0000
Orthosulfamuron + quinclorac	491	87	99	92-	0.0001
Penoxsulam	40	97	99	98	0.4548
42 DAT					
None	—		—	98	—
Bensulfuron	43	89	99	98	0.4488
Bispyribac	34	98	99	98	0.4362
Halosulfuron	53	98	99	98	0.4349
Imazosulfuron	212	92	99	98	0.3945
Orthosulfamuron	74	85	99	98	0.2914
Orthosulfamuron + quinclorac	491	91	99	98	0.2645
Penoxsulam	40	98	99	98	0.5204

[a]Evaluation dates for each respective herbicide mixture
[b]Observed means followed by a minus (-) sign indicate an antagonistic response and are significantly different from Blouin's modified Colby's expected responses at the 5% level. Means response. No (–) sign indicates a neutral response.
[c]$P < 0.05$ indicated an antagonistic response, $P > 0.05$ indicates a neutral response
[d]DAT, days after treatment

However, by 28 DAT, the initial antagonism observed at 14 DAT was overcome for activity on rice flatsedge for all treatments, except when treated with florpyrauxifen plus orthosulfamuron-containing products (Table 4.4). The antagonism observed at 14 DAT persisted for rice flatsedge control at 28 DAT when treated with florpyrauxifen plus orthosulfamuron-containing products with an observed control of 91 to 92%, compared with an expected control of 99%. Orthosulfamuron also severely antagonized florpyrauxifen activity on barnyardgrass (Table 4.2) and was the only product to antagonize florpyrauxifen activity on yellow nutsedge (Table 4.3) at 28 DAT, indicating this product should be avoided when considering mixture options for florpyrauxifen.

At 42 DAT, activity on rice flatsedge treated with all mixtures indicated a neutral response (Table 4.4). Observed control for each mixture was 98%, compared with an expected control of 99%. These data suggest the herbicide activity of florpyrauxifen mixed with ALS-inhibiting herbicides applied on rice flatsedge can be slower than the activity of the products independently applied on rice flatsedge; however, initial antagonism observed can be overcome by 28 to 42 DAT. Additionally, these data at 42 DAT are consistent with the findings of Miller and Norsworthy (2018a) suggesting ALS-inhibiting herbicides did not antagonize florpyrauxifen activity for yellow nutsedge control.

Hemp sesbania control was greater than 97% when treated with each herbicide applied alone at each evaluation date (Table 4.5). At 14 DAT, a neutral interaction was observed for hemp sesbania treated with all mixtures evaluated except florpyrauxifen plus bensulfuron, which was antagonistic. The antagonism resulted in an observed control of 87%, compared with an expected control of 99%. Similarly, Shaw and Arnold (2002) reported hemp sesbania activity was antagonized when treated with glyphosate mixed with chlorimuron, chloransulam-methyl, imazaquin, and pyrithiobac.

At 28 DAT, the antagonism observed with the bensulfuron mixture was overcome, and hemp sesbania treated with every mixture except florpyrauxifen plus orthosulfamuron plus quinclorac indicated a neutral response (Table 4.5). Observed control for hemp sesbania treated with florpyrauxifen plus orthosulfamuron plus quinclorac was 87%, compared with an expected control of 99%. Similar to barnyardgrass (Table 4.2), yellow nutsedge (Table 4.3), and rice flatsedge (Table 4.4) control at 28 DAT, these data suggest orthosulfamuron-containing products can antagonize florpyrauxifen activity and this mixture should be avoided.

At 42 DAT, a neutral interaction was observed for hemp sesbania control when treated with all mixtures (Table 4.5). Observed and expected control for hemp sesbania treated with each mixture was 98 to 99%, similar to what was observed for yellow nutsedge and rice flatsedge control. Furthermore, like yellow nutsedge (Table 4.3) and rice flatsedge (Table 4.4) control, any initial antagonism observed for hemp sesbania control at 14 or 28 DAT can be overcome by 42 DAT. A similar response to hemp sesbania was observed for Indian jointvetch control at all evaluation dates.

PVL01 rice injury was less than 5% across all evaluations (data not shown). Rough rice yield was 4130 kg ha^{-1} when PVL01 rice was treated with florpyrauxifen applied alone (Table 4.6). A similar yield response was observed for rice treated with all mixtures except florpyrauxifen plus orthosulfamuron. PVL01 rice treated with florpyrauxifen plus orthosulfamuron was reduced to 3060 kg ha^{-1}, and is likely a consequence of the antagonism observed for barnyardgrass (Table 4.2), yellow nutsedge (Table 4.3), and rice flatsedge (Table 4.4) control. Although antagonistic interactions were observed for all other mixtures, these yield

Table 4.5. Hemp sesbania control with florpyrauxifen applied alone or mixed with ALS-inhibiting herbicides labeled for use in rice production using Blouin's modified Colby's analysis in 2017 and 2018.

		Florpyrauxifen-benzyl (g ai ha^{-1})			
		0	29		
Mixture Herbicide[a]	Rate	Observed	Expected	Observed[b]	P value[c]
	g ai ha^{-1}	—— % of control ——			
14 DAT[d]					
None	—	0	—	98	—
Bensulfuron	43	98	99	87-	0.0001
Bispyribac	34	97	99	96	0.0637
Halosulfuron	53	98	99	98	0.4635
Imazosulfuron	212	98	99	98	0.3404
Orthosulfamuron	74	98	99	98	0.3994
Orthosulfamuron + quinclorac	491	98	99	97	0.4380
Penoxsulam	40	98	99	98	0.4301
28 DAT					
None	—	0	—	98	—
Bensulfuron	43	97	99	98	0.3453
Bispyribac	34	98	99	98	0.4946
Halosulfuron	53	98	99	98	0.4263
Imazosulfuron	212	98	99	98	0.3422
Orthosulfamuron	74	96	99	98	0.5001
Orthosulfamuron + quinclorac	491	97	99	87-	0.0001
Penoxsulam	40	98	98	99	0.3693
42 DAT					
None	—	0	—	99	—
Bensulfuron	43	97	99	99	0.5663
Bispyribac	34	98	99	99	0.5618
Halosulfuron	53	98	99	99	0.5976
Imazosulfuron	212	98	99	98	0.4599
Orthosulfamuron	74	97	99	98	0.5295
Orthosulfamuron + quinclorac	491	98	99	98	0.5271
Penoxsulam	40	98	99	99	0.5991

[a]Evaluation dates for each respective herbicide mixture

[b]Observed means followed by a minus (-) sign indicate an antagonistic response and are significantly different from Blouin's modified Colby's expected responses at the 5% level. Means response. No (–) sign indicates a neutral response.

[c]$P < 0.05$ indicated an antagonistic response, $P > 0.05$ indicates a neutral response

[d]DAT, days after treatment

data suggest the competition between PVL01 rice and the antagonized weeds was similar to the competition between the weed escapes and rice treated with florpyrauxifen applied alone.

Table 4.6. Rough rice yield for 'PVL01' rice treated with florpyrauxifen and each respective mixture in 2017 and 2018.

		Florpyrauxifen-benzyl (g ai ha^{-1})	
Mixture herbicide[a]	Rate	0	120
	g ai ha^{-1}	kg ha^{-1}	
None	—	510 f	4130 ab
Bensulfuron	43	1170 ef	4430 ab
Bispyribac	34	4190 ab	5330 a
Halosulfuron	53	1660 def	4140 ab
Imazosulfuron	212	1110 ef	3950 ab
Orthosulfamuron	74	1060 ef	3060 cd
Orthosulfamuron + quinclorac	491	2590 cde	4170 ab
Penoxsulam	40	2590 cde	4300 ab

[a]Respective herbicide mixtures
[b]Means followed by a common letter are not significantly different at P = 0.05 with the use of Tukey's HSD

In conclusion, all of the ALS-inhibiting herbicides evaluated in this study can antagonize florpyrauxifen activity when applied in a mixture, especially when barnyardgrass is present (Table 4.2). At 14 and 28 DAT, these data contradict Miller and Norsworthy (2018a) suggesting no herbicide antagonism when florpyrauxifen was applied in a mixture with various ALS-inhibiting herbicides for barnyardgrass (Table 4.2), yellow nutsedge (Table 4.3), and hemp sesbania control (Table 4.5). However, some results of this study were similar to Miller and Norsworthy (2018a) at 42 DAT, indicating no antagonistic interactions for yellow nutsedge, rice flatsedge, and hemp sesbania control. Although antagonism can be overcome and rice yields can be similar when treated with the herbicides applied alone, caution should be taken when considering mixing florpyrauxifen with an ALS-inhibiting herbicide. It has been reported in several studies that antagonized barnyardgrass can compete with rice and result in significant yield reductions (Rustom et al. 2018, 2019). In addition, applications of orthosulfamuron should be avoided in a mixture with this new technology to avoid rough rice yield reductions (Table 4.6). Research has suggested ALS-inhibiting herbicides can reduce translocation of herbicides with grass activity when applied in a mixture, resulting in an antagonistic response (Ferreira 1995). Furthermore, the barnyardgrass antagonism observed in this study (Table 4.2) could be a result of reduced florpyrauxifen translocation due to interference by ALS-inhibiting products; however, this hypothesis will need with further investigation.

Chapter 5
Florpyrauxifen-benzyl Mixture Interactions with Contact Herbicides Used in Rice Production

Introduction

Rice (*Oryza sativa* L.) is the world's largest food crop that provides approximately 20% of the calories consumed worldwide (Greenland 1997; Kubo and Purevdorj 2004). Louisiana is the third largest rice producing state in the United States, with 172,000 hectares planted in 2019 (USDA NASS 2020). The majority of the rice in Louisiana is planted in the northeast and southwest regions of the state; however, production strategies can vary based on soil type, weather conditions, weed species, and tradition (Bollich 1992). In both areas of the state, as well as worldwide, successful weed management programs are often the driving force to maximize yield and economic returns for rice producers (Carlson et al. 2011; Chauhan 2012; Rodenburg and Johnson 2009).

Implementing weed management strategies through the use of cultural, mechanical, or chemical methods is imperative to produce a successful rice crop (Jordan and Sanders 1999). Almost every hectare of rice produced in the United States receives an annual herbicide application, with most hectares under production receiving multiple applications per year (Gianessi and Reigner 2007). In addition, it is estimated that producers spend $7 billion annually for herbicides and their application. As a consequence of reliance on herbicides, herbicide-resistant weeds present a major threat to rice producers in the United States (Owen and Zelaya 2005). Barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv] resistance has been reported for several modes of action such as propanil (Carey et al. 1995), quinclorac (Malik et al. 2010), and imazethapyr (Riar et al. 2013). In addition, rice flatsedge (*Cyperus iria* L.) and yellow nutsedge

(*Cyperus esculentus* L.) resistance to ALS-inhibiting herbicides has been reported (Riar et al. 2015; Tehranchian et al. 2015).

Barnyardgrass is a summer annual bunchgrass member of the Poaceae family that has historically been one of the most troublesome weeds interfering with rice production (Bryson and Delfice 2009; Holm et al. 1977; Noda et al. 1968; Norsworthy et al. 2013; Smith 1968, 1974). Barnyardgrass thrives in areas with moist soil and high nitrogen content and is a fierce competitor with rice for nutrients, water, and space (Bagavathiannan et al. 2012; Chin 2001; Smith 1968, 1974). In addition, some biotypes have adapted to germinate under water (Smith 1988). It has been reported that barnyardgrass can potentially remove up to 80% of available soil nitrogen (Noda et al. 1968). The phenotypic characteristics of barnyardgrass biotypes can vary greatly by expressing differences in plant height, size and number of seeds, shape of panicles, and/or expression of awns (Barrett 1983; Smith 1988; Smith et al. 1977).

Yellow nutsedge and rice flatsedge are members of the Cyperaceae family that can tolerate high soil moisture and are commonly found infesting rice cropping systems (Bendixen and Namdihalli 1987; Webster 2014). Both weeds have the C_4 photosynthetic pathway that provides a more efficient and competitive advantage for nutrients and light over rice, which has the less efficient C_3 pathway (Chauhan and Johnson 2010; Sage 2000; Smith 1988). Consequently, yellow nutsedge and rice flatsedge can reduce rice yields by 41 and 64%, respectively (Dhammu and Sandhu 2002; Keeley 1987). Yellow nutsedge is a perennial weed that primarily reproduces by tubers that has little to no viable seed; however, rice flatsedge is an annual weed that reproduces and spreads primarily through seed production (Galinato et al. 1999; Thullen and Keeley 1979).

Hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh] is a member of the Fabaceae family that was reported by Smith (1988) as the most competitive broadleaf weed encountered by rice, and 12 plants m^{-2} can reduce rice yield up to 50%. Additionally, the presence of hemp sesbania seeds in harvested rice grain negatively impact the value of the harvested crop. Hemp sesbania is identified by alternate pinnately compound leaves with opposite leaflets, 2- to 6-inflorescences on racemes borne in leaf axils, yellow petals up to 1.5 cm long, beak shaped or curved leguminous fruits up to 20-cm long, brown seeds that are 2 times longer than wide, and growing up to 4-m tall (Bryson and Delfice 2009).

Similar to hemp sesbania, Indian jointvetch (*Aeschynomene* indica L.) is a common weed interfering with rice production (Webster 2014). This member of the Fabaceae family can grow to 2.5 m tall and is identified by evenly pinnately compound leaves, sensitive leaflets that fold when touched, lance-shaped stipules, inflorescences up to 10 cm long subtended by a toothed bract, and kidney-shaped seeds (Bryson and DeFelice 2009). Smith (1988) reported northern jointvetch (*A. virginica* L.), a close relative of Indian jointvetch, is the second most competitive broadleaf weed in rice and 29 plants m^{-2} can reduce rough rice yields 50%. Similar to hemp sesbania, the presence of Indian jointvetch seeds in harvested rice grain can negatively impact the overall value of the crop.

The utilization of herbicides with alternate modes of action would serve as a beneficial component to an overall weed management program (Norsworthy et al. 2012). Florpyraixifen-benzyl (florpyrauxifen) was commercialized Corteva Agriscience™ in 2018, representing a new structural class of synthetic auxin herbicides in the arylpicolinate family (Epp et al. 2016). Unlike other synthetic auxin herbicides such as 2,4-dichlorophenoxy acetic acid (2,4-D), florpyrauxifen exhibits strong binding affinity for different auxin signaling F-box proteins than other synthetic auxin herbicides, signifying a unique mechanism of action (Bell et al. 2005; Epp et al. 2016; Jeschke 2015b). In order to become active in the plant, florpyrauxifen must be converted to florpyrauxifen-acid through enzymatic hydrolysis; therefore, soil moisture conditions can impact the herbicide's activity on target weeds (Epp et al. 2016; Jeschke 2015a; Miller and Norsworthy 2018b).

There are several auxin herbicides used in rice production such as 2,4-D, triclopyr, and quinclorac (Shaner 2014). Triclopyr and 2,4-D are primarily used for broadleaf weed management and exhibit little to no activity on grasses or sedges. Quinclorac has activity on grasses; however, little to no activity on sedges and barnyardgrass resistance can be problematic (Malik et al. 2010; Shaner 2014). Florpyrauxifen exhibits broad spectrum of activity on broadleaf, grass, and sedge weeds; however, activity can vary based on weed species and soil moisture (Miller and Norsworthy 2018a; 2018b). Miller and Norsworthy (2018b) reported approximately half of florpyrauxifen applied at 7.5% soil moisture was absorbed by barnyardgrass and yellow nutsedge, compared with 86 to 97% absorption at 60% soil moisture. In addition, only 61 to 67% of florpyrauxifen applied to barnyardgrass and yellow nutsedge was metabolically converted to florpyrauxifen-acid in low soil moisture conditions compared with 83% conversion by hemp sesbania.

The economic value of applying herbicides in mixtures is well documented (Carlson et al. 2011; Pellerin et al. 2003, Pellerin and Webster 2004; Webster et al. 2012). Weeds treated with herbicides applied in a mixture will have one of three responses: synergistic, antagonistic, or neutral (Berenbaum 1981; Blouin et al. 2010; Fish et al. 2015, 2016; Hatzios and Penner 1985; Morse 1978; Nash 1981; Rustom et al. 2018, 2019; Streibig et al. 1998). Herbicide antagonism is defined by Beste (1983) as "an interaction of two or more chemicals such that the effect when combined is less than the predicted effect based on each chemical applied separately." Synergism is the inverse of antagonism, where the effect when combined exceeds the predicted effect based on the herbicides applied separately. A neutral or additive response is indicated by similar effects when herbicides are applied combined or alone.

Herbicides with grass activity have a history of antagonism when applied in a mixture with other herbicides in rice production (Rustom et al. 2018; 2019; Scherder et al. 2005; Scott 2002; Webster et al. 2019; Zhang et al. 2005). Antagonism of quizalofop activity by several Acetolactate synthase (ALS) inhibiting (Rustom et al. 2018), contact (Rustom et al. 2019), and auxin (Webster et al. 2019) herbicides on barnyardgrass has been reported. Zhang et al. (2005) suggested fenoxaprop-p-ethyl activity on barnyardgrass can be antagonized by carfentrazone, halosulfuron, bensulfuron, and triclopyr. Additional antagonism of barnyardgrass activity in rice production has been reported by Fish et al. (2015) when imazethapyr was mixed with propanil plus thiobencarb.

Antagonistic, synergistic, or neutral responses to herbicide mixtures are typically determined under the guidelines of Colby's (1967) procedure by calculating an expected response, based on the activity of the herbicides applied alone, to be compared with the observed response of the herbicides applied together. Blouin et al. (2004) suggested the expected response is a nonlinear function of the means for the herbicides applied alone, then the standard linear model methodology used in Colby's (1967) tests of hypotheses does not apply; therefore, the Blouin et al. (2004) model is more sensitive than Colby's (1967) linear model in detecting significant differences in herbicide response. Furthermore, Blouin et al. (2010) further modified the nonlinear model into an augmented mixed-model, which proved to be more sensitive than the

Blouin et al. (2004) nonlinear mixed model when observing fenoxaprop-p-ethyl mixtures with various rice herbicides.

Florpyrauxifen represents a new mechanism of action for use in rice production with activity on a broad spectrum of weeds. This new technology will be a beneficial tool for rice producers; however, research needs to be conducted to understand the activity of florpyrauxifen mixed with other herbicides when applied on weeds commonly interfering with rice production. The responses observed will aid in developing weed management strategies for producers choosing to utilize this new technology and rotate herbicide modes of action. The overall objective of this research is to evaluate the activity of florpyrauxifen and contact herbicides when applied alone or in a mixture in rice production.

Materials and Methods

A field study was conducted in 2017 and 2018 at the H. Rouse Caffey Rice Research Station (RRS) near Crowley, Louisiana to evaluate the activity of florpyrauxifen and contact herbicides when applied independently or in a mixture. The soil type at the RRS is a Crowley silt loam (fine smectic, thermic Typic Albaqualfs) with a pH of 6.4 and 1.4% organic matter. Field preparation consisted of a fall and spring disking followed by two passes in opposite directions with a two-way bed conditioner consisting of rolling baskets and S-tine harrows set at 6 cm depth.

Plot size was 1.5- by 5.2-m with eight-19.5 cm drill-seeded rows planted with ‘PVL01’, an acetyl-coenzyme A herbicide resistant long grain rice, at a rate of 67 kg ha^{-1}. The research area was surface irrigated to a depth of 2.5-cm 24-hours after planting. A permanent 10-cm flood was established when the rice reached the five-leaf to one-tiller stage, and was maintained until two weeks prior to harvest. The area was naturally infested with barnyardgrass at 100- to 200-

plants m^{-2} with 2- to 3- leaves and 5- to 13-cm tall, yellow nutsedge at 5- to 15-plants m^{-2} with 3- to 5-leaves and 8- to 23-cm tall, rice flatsedge at 100- to 150-plants m^{-2} with 3- to 5-leaves and 3- to 10-cm tall, hemp sesbania at 15- to 20-plants m^{-2} with 1- to 2- leaves and 5- to 8-cm tall, and Indian jointvetch at 10- to 20-plants m^{-2} with 2- to 3 leaves and 5- to 8-cm tall.

The study was a randomized complete block design with a factorial arrangement of treatments with four replications. Factor A was florpyrauxifen applied at 29 g ai ha^{-1} or no florpyrauxifen (Table 5.1). Factor B was bentazon applied at 1050 g ai ha^{-1}, carfentrazone applied at 18 g ai ha^{-1}, propanil applied at 3360 g ai ha^{-1}, saflufenacil applied at 25 g ai ha^{-1}, thiobencarb applied at 3360 g ai ha^{-1}, or no mixture herbicide (Table 5.1). A methylated seed oil (MSO) was added to each herbicide application at 1% v/v. Each herbicide application was applied when the rice was at the three- to four-leaf growth stage with a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} with five flat-fan 110015 nozzles spaced at 35 cm.

Visual evaluations for this study included crop injury and barnyardgrass, yellow nutsedge, rice flatsedge, hemp sesbania, and Indian jointvetch control expressed as a percent with 0 = no injury or control and 100 = complete plant death at 14, 28, and 42 days after treatment (DAT). PVL01 rice plant height was recorded from four plants in each plot measured from the ground to the tip of the extended panicle (data not shown). The center four rows of rice were harvested with a Mitsubishi VM3 (Mitsubishi Corporation, 3-1, Marunouchi 2- chome, Chiyoda-ky, Tokyo, Japan) plot combine and grain yield was adjusted to 12% moisture.

Control data collected were analyzed using the Blouin et al. (2010) augmented mixed model to determine synergistic, antagonistic, or neutral responses for herbicide mixtures by comparing an expected control calculated based on activity of each herbicide applied alone to an observed control. Rough rice yield data were analyzed using the MIXED procedure in SAS (release 9.4 SAS Institute, Cary, NC). The fixed effects for all models were the herbicide treatments and evaluation timing. The random effects were years, replication within years, and plots. Considering year or combination of years as a random effect accounts for different environmental conditions each year having an effect on herbicide treatments for that year (Carmer et al. 1989; Hager et al. 2003). Normality of effects over all DAT was checked with the use of the UNIVARIATE procedure of SAS and significant normality problems were not observed.

Table 5.1. Herbicide information for all products used in experiment[a]

Herbicide common name	Herbicide trade name	Rate g ai ha^{-1}	Manufacturer
Bentazon	Basagran	1050	BASF Corporation, Research Triangle Park, NC
Carfentrazone	Aim	18	FMC Corporation, Philadelphia, PA
Florpyrauxifen-benzyl	Loyant	29	Corteva Agriscience, Indianapolis, IN
Propanil	Stam M4	3360	UPL North America Inc., King of Prussia, PA
Saflufenacil	Sharpen	25	BASF Corporation, Research Triangle Park, NC
Thiobencarb	Bolero	3360	Valent U.S.A. Corporation, Walnut Creek, CA

[a]All treatments were applied with methylated seed oil (MSO; Leci-Tech, Loveland Products, Loveland, CO) at 1% v/v.

Results and Discussion

At 14 DAT, an antagonistic interaction occurred when barnyardgrass was treated florpyrauxifen mixed with all contact herbicides except carfentrazone, which indicated a neutral response (Table 5.2). Rustom et al. (2019) reported similar interactions when barnyardgrass treated with carfentrazone mixed with quizalofop. A severely antagonistic response was observed for barnyardgrass treated with florpyrauxifen mixed with propanil, with an expected control of 89% reduced to an observed control of 41%, with a P-value of 0.0001. Rustom et al. (2019) observed a similar response for barnyardgrass treated with quizalofop mixed with propanil. In addition, the expected control for barnyardgrass treated with florpyrauxifen mixed with bentazon, saflufenacil, or thiobencarb was 76 to 81%, compared with an observed control of 54 to 58%.

A similar response was observed for barnyardgrass activity at 28 DAT when carfentrazone was the only contact herbicide that did not antagonize florpyrauxifen (Table 5.2). The expected control of propanil was 89% and reduced to an observed control of 32%. Ottis et al. (2005) reported propanil can interact with the enzyme responsible for converting ACCase herbicides to the active form in weeds, resulting in an antagonistic response. Furthermore, this could possibly explain the antagonism observed with florpyrauxifen mixed with propanil, considering florpyrauxifen must also be converted to the active form. In addition to propanil antagonism, the expected control for barnyardgrass treated with florpyrauxifen mixed bentazon, saflufenacil, or thiobencarb was 79 to 83%, compared with an observed control of 50 to 59%.

At 42 DAT, a slightly antagonistic response was observed for barnyardgrass treated with florpyrauxifen mixed with carfentrazone, suggesting barnyardgrass can overcome the initial injury observed at 14 and 28 DAT (Table 5.2). Observed barnyardgrass control for this mixture was 67%, compared with an expected control of 79%, and a P-value of 0.0261. In addition, all other contact herbicides mixed with florpyrauxifen were antagonistic for barnyardgrass activity, similar to what was observed at 14 and 28 DAT. These data suggest bentazon, carfentrazone, propanil, saflufenacil, and thiobencarb should be avoided when considering mix partners with florpyrauxifen for barnyardgrass management.

Table 5.2. Barnyardgrass control with florpyrauxifen applied alone or mixed with contact herbicides labeled for use in rice production using Blouin's modified Colby's analysis in 2017 and 2018.

		Florpyrauxifen-benzyl (g ai ha^{-1})			
		0	29		
Mixture Herbicide[a]	Rate	Observed	Expected	Observed[b]	P value[c]
	g ai ha^{-1}	% of control			
14 DAT[d]					
None	—	0	—	76	—
Bentazon	1050	0	76	58-	0.0004
Carfentrazone	18	0	76	69	0.1384
Propanil	3360	52	89	41-	0.0001
Saflufenacil	25	0	76	54-	0.0001
Thiobencarb	3360	18	81	56-	0.0001
28 DAT					
None	—	0	—	79	—
Bentazon	1050	0	79	59-	0.0001
Carfentrazone	18	0	79	70	0.0628
Propanil	3360	51	89	32-	0.0001
Saflufenacil	25	0	79	55-	0.0001
Thiobencarb	3360	19	83	50-	0.0001
42 DAT					
None	—	0	—	79	—
Bentazon	1050	0	79	57-	0.0001
Carfentrazone	18	0	79	67-	0.0261
Propanil	3360	47	81	32-	0.0001
Saflufenacil	25	0	79	49-	0.0001
Thiobencarb	3360	12	89	53-	0.0001

[a]Evaluation dates for each respective herbicide mixture
[b]Observed means followed by a minus (-) sign indicate an antagonistic response and are significantly different from Blouin's modified Colby's expected responses at the 5% level. Means response. No (–) sign indicates a neutral response.
[c]$P < 0.05$ indicated an antagonistic response, $P > 0.05$ indicates a neutral response
[d]DAT, days after treatment

An antagonistic response was observed for yellow nutsedge treated with a mixture of florpyrauxifen and saflufenacil at 14 DAT (Table 5.3). Expected control was 87%, compared with an observed control of 75% and a P-value of 0.0126. However, unlike barnyardgrass activity, yellow nutsedge treated with all other mixtures indicated a neutral response at 14 DAT.

Table 5.3. Yellow nutsedge control with florpyrauxifen applied alone or mixed with contact herbicides labeled for use in rice production using Blouin's modified Colby's analysis in 2017 and 2018.

		Florpyrauxifen-benzyl (g ai ha^{-1})			
		0	29		
Mixture Herbicide[a]	Rate	Observed	Expected	Observed[b]	P value[c]
	g ai ha^{-1}	% of control			
14 DAT[d]					
None	—	0	—	77	—
Bentazon	1050	89	97	89	0.1250
Carfentrazone	18	4	78	69	0.0672
Propanil	3360	42	87	78	0.0640
Saflufenacil	25	43	87	75-	0.0126
Thiobencarb	3360	13	81	71	0.0629
28 DAT					
None	—	0	—	87	—
Bentazon	1050	93	99	96	0.5901
Carfentrazone	18	6	88	87	0.8643
Propanil	3360	44	93	87	0.2381
Saflufenacil	25	39	92	86	0.2398
Thiobencarb	3360	14	89	87	0.6935
42 DAT					
None	—	0	—	88	—
Bentazon	1050	95	99	96	0.5902
Carfentrazone	18	14	89	89	0.9392
Propanil	3360	48	94	84	0.0631
Saflufenacil	25	62	95	90	0.2990
Thiobencarb	3360	19	90	88	0.7135

[a]Evaluation dates for each respective herbicide mixture
[b]Observed means followed by a minus (-) sign indicate an antagonistic response and are significantly different from Blouin's modified Colby's expected responses at the 5% level. Means response. No (–) sign indicates a neutral response.
[c]$P < 0.05$ indicated an antagonistic response, $P > 0.05$ indicates a neutral response
[d]DAT, days after treatment

A similar response was observed at 28 and 42 DAT when a neutral response was observed for yellow nutsedge treated with all mixtures, indicating the antagonism previously observed when florpyrauxifen was mixed with saflufenacil was overcome. These data are similar to Miller and

Norsworthy (2018a) reporting no antagonism when yellow nutsedge was treated with florpyrauxifen mixed with various herbicides in rice production, suggesting contact herbicides can be used in a mixture with florpyrauxifen when yellow nutsedge is present.

A similar response to yellow nutsedge control was observed for rice flatsedge control, except all interactions for rice flatsedge treated with each mixture were neutral at 14 DAT (Table 5.4). For each mixture, the expected control at 14 DAT was similar to the observed control of 89 to 94%. Similarly, the observed and expected rice flatsedge control was 90 to 99% at 28 and 42 DAT for all mixtures. These data suggest bentazon, carfentrazone, propanil, saflufenacil, and thiobencarb will not negatively impact the activity of florpyrauxifen on rice flatsedge. Lanclos et al. (2002) observed similar rice flatsedge activity when glufosinate was applied in a mixture with propanil and propanil plus molinate.

Table 5.4. Rice flatsedge control with florpyrauxifen applied alone or mixed with contact herbicides labeled for use in rice production using Blouin's modified Colby's analysis in 2017 and 2018.

		Florpyrauxifen-benzyl (g ai ha^{-1})			
		0	29		
Mixture Herbicide[a]	Rate	Observed	Expected	Observed[b]	P value[c]
	g ai ha^{-1}	% of control			
14 DAT[d]					
None	—	0	—	90	—
Bentazon	1050	89	99	93	0.1170
Carfentrazone	18	4	90	82	0.1147
Propanil	3360	47	95	94	0.9649
Saflufenacil	25	48	95	91	0.4231
Thiobencarb	3360	10	91	89	0.6383
28 DAT					
None	—	0	—	98	—
Bentazon	1050	96	99	99	0.7354
Carfentrazone	18	9	98	97	0.8349
Propanil	3360	54	99	98	0.8523
Saflufenacil	25	55	99	90	0.0370

Table 5.4 cont'd

Table 5.4 cont'd

		Florpyrauxifen-benzyl (g ai ha^{-1})			
		0	29		
Mixture Herbicide[a]	Rate	Observed	Expected	Observed[b]	P value[c]
	g ai ha^{-1}		% of control		
Thiobencarb	3360	12	98	97	0.8256
42 DAT					
None	—	0	—	97	—
Bentazon	1050	97	99	96	0.2930
Carfentrazone	18	12	97	98	0.8948
Propanil	3360	47	98	95	0.4808
Saflufenacil	25	68	99	98	0.8611
Thiobencarb	3360	27	97	98	0.9365

[a]Evaluation dates for each respective herbicide mixture
[b]Observed means followed by a minus (-) sign indicate an antagonistic response and are significantly different from Blouin's modified Colby's expected responses at the 5% level. Means response. No (–) sign indicates a neutral response.
[c]$P < 0.05$ indicated an antagonistic response, $P > 0.05$ indicates a neutral response
[d]DAT, days after treatment

A neutral response was observed for Indian jointvetch treated with each florpyrauxifen mixture across all evaluations, and neither observed or expected control was below 98% at any DAT (Table 5.5). The response of hemp sesbania, a relative to Indian jointvetch, was similar to Indian jointvetch, with no observed or expected control below 97% at all DAT (data not shown). These data are similar to Miller and Norsworthy (2018a) reporting no antagonistic interactions indicated by hemp sesbania, when treated with florpyrauxifen mixed with contact or systemic herbicides. In addition, Miller and Norsworthy (2018b) highlight the high levels of sensitivity of plants in the Fabaceae family to florpyrauxifen, reporting a greater amount of florpyrauxifen was converted to the active acid form by hemp sesbania when compared with barnyardgrass or yellow nutsedge.

PVL01 rice injury was less than 5% across all evaluations (data not shown). Rough rice yield for PVL01 treated with florpyrauxifen applied alone was 4870 kg ha^{-1}. A similar response

Table 5.5. Indian jointvetch control with florpyrauxifen applied alone or mixed with contact herbicides labeled for use in rice production using Blouin's modified Colby's analysis in 2017 and 2018.

		Florpyrauxifen-benzyl (g ai ha^{-1})			
		0	29		
Mixture Herbicide[a]	Rate	Observed	Expected	Observed[b]	P value[c]
	g ai ha^{-1}	—— % of control ——			
14 DAT[d]					
None	—	0	—	97	—
Bentazon	1050	96	99	98	0.1647
Carfentrazone	18	97	99	98	0.1555
Propanil	3360	88	99	98	0.1810
Saflufenacil	25	97	99	98	0.1890
Thiobencarb	3360	96	99	98	0.1632
28 DAT					
None	—	0	—	98	—
Bentazon	1050	98	99	98	0.1250
Carfentrazone	18	98	99	98	0.2149
Propanil	3360	94	99	98	0.1406
Saflufenacil	25	98	99	98	0.0821
Thiobencarb	3360	95	99	98	0.1093
42 DAT					
None	—	0	—	99	—
Bentazon	1050	98	99	98	0.2461
Carfentrazone	18	98	99	98	0.1766
Propanil	3360	95	99	98	0.2587
Saflufenacil	25	98	99	99	0.3324
Thiobencarb	3360	97	99	98	0.1778

[a]Evaluation dates for each respective herbicide mixture
[b]Observed means followed by a minus (-) sign indicate an antagonistic response and are significantly different from Blouin's modified Colby's expected responses at the 5% level. Means response. No (–) sign indicates a neutral response.
[c]$P < 0.05$ indicated an antagonistic response, $P > 0.05$ indicates a neutral response
[d]DAT, days after treatment

observed for PVL01 treated with florpyrauxifen mixed with carfentrazone, the only mixture that was not antagonistic for barnyardgrass control at 14 or 28 DAT. Although this mixture was antagonistic for barnyardgrass control at 42 DAT, the antagonism did not impact rough rice yield, indicating caution should be taken when considering carfentrazone as a mix partner with florpyrauxifen. However, when compared with florpyrauxifen applied alone, rough rice yield was decreased to 1650 to 3680 kg ha^{-1} when PVL01 rice was treated with all other mixtures. Yield of PVL01 rice treated with florpyrauxifen mixed with propanil was similar to the nontreated rice as well as rice treated with each of the contact herbicides applied alone which is likely due to these treatments having little to no activity on barnyardgrass. A similar yield reduction was observed by Rustom et al. (2018, 2019) when barnyardgrass was treated with quizalofop mixed with bispyribac, penoxsulam, or propanil.

Table 5.6. Rough rice yield for 'PVL01' rice treated with florpyrauxifen and each respective mixture in 2017 and 2018.

		Florpyrauxifen-benzyl (g ai ha^{-1})	
Mixture herbicide[a]	Rate	0	120
	g ai ha^{-1}	kg ha^{-1}	
None	—		4870 a
Bentazon	1050	800 d	3270 bc
Carfentrazone	18	680 d	4330 ab
Propanil	3360	1770 d	1650 d
Saflufenacil	25	1130 d	3030 c
Thiobencarb	3360	830 d	3680 bc

[a]Respective herbicide mixtures
[b]Means followed by a common letter are not significantly different at P = 0.05 with the use of Tukey's HSD

In conclusion, understanding these mixture interactions will aid in developing weed management strategies for producers who utilize this new technology. Miller and Norsworthy (2018a) suggested there were no antagonistic interactions when barnyardgrass was treated with florpyrauxifen mixed with several herbicides labeled for use in rice production. The antagonistic interactions reported in this study for barnyardgrass control (Table 5.2) contradict Miller and Norsworthy (2018a); however, the neutral interactions for yellow nutsedge (Table 5.3) and hemp sesbania (Table 5.5) control are consistent with the findings of Miller and Norsworthy (2018a). These results prove the sensitivity of Blouin's (2010) modified Colby's procedure for analyzing antagonism or synergism, compared with the use of an LSD in Colby's (1967) method. Furthermore, these data suggests florpyrauxifen can be used in a mixture with contact herbicides where yellow nutsedge, rice flatsedge, hemp sesbania, and Indian jointvetch are present. However, if barnyardgrass is present, mixing florpyrauxifen with bentazon, propanil, saflufenacil, or thiobencarb should be avoided to prevent antagonistic interactions and consequential rough rice yield reductions.

Chapter 6
Evaluation of Florpyrauxifen-benzyl and Halosulfuron Plus Prosulfuron Applied in a Salvage Situation in Louisiana Rice

Introduction

Rice, the world's largest food crop, was domesticated in China between 8000 and 10000 years ago and has since supported a greater number of people for a longer period of time than any other crop (Greenland 1997; Sweeney and McCouch 2007). Rice cultivation in the United States began in the tidewater regions of the Carolina colonies in 1685 and has since expanded to Arkansas, California, Louisiana, Mississippi, Texas, and Missouri (Smith and Dilday 2003; USDA NASS 2020). In 2019, rice was planted on approximately 172,000 hectares in Louisiana, the third largest rice producing state in the United States (USDA NASS 2020).

Weed management programs through the use of cultural, mechanical, or chemical methods are crucial to maximize yield and economic returns for rice producers (Jordan and Sanders 1999). Approximately 98% of the rice produced in the United States receives an annual herbicide application, with most hectares receiving multiple applications annually (Gianessi and Reigner 2007). Additionally, it is estimated that producers spend $7 billion annually for herbicides and their application.

It is well known that one of the primary benefits of flooding rice is weed control, considering rice tolerates hypoxic conditions better than most weeds (Helms 1994; Masson et al. 2001; Smith et al. 1977). Like other crops, controlling weeds early in the growing season prior to flooding is crucial to protect rice yields (Fischer et al. 1993; Page et al. 2012; Smith 1968, 1988); however, it is understood this approach sometimes fails and producers must rely on postflood herbicide applications to control weeds. Late season postflood weed control is commonly referred to as a salvage treatment and can be problematic due to the advanced growth stages of target weeds and poor herbicide spray coverage as a result of the developing rice and weed canopy (Bond and Walker 2012; Webster 2014). These salvage situations often occur after the last planned herbicide application during the growing season. Oftentimes, rice is past the green ring or panicle initiation growth stage of rice growth and there are limited products labeled for use at this time.

Hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh] and northern jointvetch [*Aeschynomene virginica* (L.) Britton, Sterns & Poggenb.] are two of the most competitive broadleaf weeds with rice and can reduce rice yields by 50% at densities of 12 and 29%, respectively, after season long competition (Smith 1988). Weeds in Fabaceae family typically have nodules to fix atmospheric nitrogen; therefore, these weeds are more competitive for light than for nitrogen. It has also been reported that hemp sesbania and northern jointvetch become more competitive with rice later in the growing season when they overtop the rice at about 12 weeks (Smith 1968). Additionally, the presence of hemp sesbania or northern jointvetch seed in harvested rice grain reduces the grade and value of the rice (Smith 1988); therefore, managing these weeds when present in a salvage situation is crucial to protect the economic value of the rice crop.

There are several other weeds commonly found infesting rice at salvage including barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv], Amazon sprangletop [*Leptochloa panicoides* (J. Presl) Hitchc], yellow nutsedge (*Cyperus esculentus* L.), rice flatsedge (*Cyperus iria* L.), Texasweed [*Caperonia palustris* (L.) A. St.-Hil.], and alligatorweed [*Alternanthera* philoxeroides (Mart.) Griseb] (Eric Webster, LSU AgCenter F. Avalon Daggett Professor of Rice Research, personal communication). The standard herbicide for broadleaf or sedge management in a salvage situation in Louisiana is halosulfuron. In addition, fenoxaprop and cyhalofop are typically used at salvage for late season grass management in rice production. Systemic herbicides are preferred in a salvage situation when possible due to poor spray coverage and the advanced growth stages of weeds. Research conducted by Bergeron et al. (2014) reported hemp sesbania control was increased with applications of systemic herbicides such as halosulfuron, halosulfuron plus thifensulfuron, imazosulfuron, orthosulfamuron, orthosulfamuron plus halosulfuron, or penoxsulam plus triclopyr, when compared with contact herbicides such as carfentrazone and propanil.

Utilizing herbicides with different modes of action would be beneficial for an overall weed management program (Norsworthy et al. 2012). Florpyrauxifen-benzyl (florpyrauxifen) is a new synthetic auxin herbicide in the arylpicolinate family that was commercialized by Corteva Agriscience™ in 2018 (Epp et al. 2016). This new herbicide exhibits different binding affinity than other auxin mimicing herbicides; thus, represents a new mechanism of action for use in rice production (Bell et al. 2005; Epp et al. 2016; Jeschke 2015b). Unlike other synthetic auxin herbicides, florpyrauxifen exhibits activity on a broad spectrum of broadleaf, grass, and sedge weeds (Miller and Norsworthy 2018a; Shaner 2014). However, florpyrauxifen must be converted to florpyrauxifen-acid in the plant through enzymatic hydrolysis to become active; therefore, the presence of soil moisture can largely impact the activity of this herbicide on several grass and sedge weeds (Epp et al. 2016; Jeschke 2015a; Miller and Norsworthy 2018b).

Additionally in 2018, Gowan Company™ released a prepackaged mixture of halosulfuron plus prosulfuron two ALS-inhibiting herbicides, for broadleaf and sedge management in rice production (Gambit® herbicide, Yuma, AZ: Gowan Company). Webster (2020) suggests this product can be applied postemergence or in a preplant burndown situation and has activity on most broadleaf and sedge weeds commonly infesting Louisiana rice. In addition to preplant burndown and postemergence use, halosulfuron plus prosulfuron applied preemergence has been beneficial for Louisiana rice producers (Eric Webster, LSU AgCenter F. Avalon Daggett Professor of Rice Research, personal communication).

These new technologies will be beneficial tools for rice producers; however, research is needed to understand the activity of these products when applied on larger weeds in advanced growth stages in a salvage situation when herbicide spray coverage could be at risk. The responses observed will aid in developing weed management strategies for producers choosing to utilize these new technologies. The overall objective of this research is to evaluate the performance of florpyrauxifen and a prepackaged mixture of halosulfuron plus prosulfuron in a salvage situation, compared with other herbicides commonly used at salvage.

Materials and Methods

A field study was conducted in 2017 and 2018 at the H. Rouse Caffey Rice Research Station (RRS) near Crowley, Louisiana to evaluate the activity of florpyrauxifen and halosulfuron plus prosulfuron compared with other herbicides commonly used in a salvage situation. The soil type at the RRS is a Crowley silt loam (fine smectic, thermic Typic Albaqualfs) with a pH of 6.4 and 1.4% organic matter. Field preparation consisted of a fall and spring disking followed by two passes in opposite directions with a two-way bed conditioner consisting of rolling baskets and S-tine harrows set at 6 cm depth.

Plot size was 1.5- by 5.2-m with eight-19.5 cm drill-seeded rows planted with ‘PVL01’, an acetyl-coenzyme A herbicide-resistant long grain rice, at a rate of 67 kg ha^{-1}. The research area was surface irrigated to a depth of 2.5-cm 24-hours after planting. A permanent 10-cm flood was established when the rice reached the five-leaf to one-tiller stage, and was maintained until two weeks prior to harvest. The research area was naturally infested with yellow nutsedge at 5-

to 10-plants m^{-2} with 6- to 9-leaves and 38- to 51-cm tall, hemp sesbania at 1- to 5-plants m^{-2} with 5- to 10-leaves and 38- to 91-cm tall, Indian jointvetch at 1- to 5-plants m^{-2} with 5- to 10-leaves and 30- to 76-cm tall, Texasweed at 2- to 8-plants m^{-2} with 10- to 15-leaves and 38- to 76-cm tall, and alligatorweed at 10- to 15-m^{-2} with 20- to 40-leaves and 46- to 76-cm tall.

The experimental design for this study was a randomized complete block. Herbicide applications were made with a CO_2-pressurized backpack sprayer calibrated to deliver 140 L ha^{-1} with five flat-fan 110015 nozzles spaced at 35 cm. A preemergence application of clomazone was applied at 340 g ai ha^{-1} to manage grasses and allow rice, broadleaf, and sedge establishment. Herbicides used and preharvest application intervals are listed in table 6.1. Treatments consisted of florpyrauxifen applied at 14.5 and 29 g ai ha^{-1}, halosulfuron applied at 53 g ai ha^{-1}, halosulfuron plus thifensulfuron appled at 53 g ai ha^{-1}, halosulfuron plus prosulfuron at 55 and 83 g ai ha^{-1}, orthosulfamuron at 94 g ai ha^{-1}, and orthosulfamuron plus quinclorac at 490 g ai ha^{-1}. Herbicide treatments were applied when PVL01 rice was at the 3- to 4- tiller growth stage approaching panicle initiation and 38- to 43-cm tall. All treatments included a methylated seed oil (MSO, Leci-Tech, Loveland Products, Loveland, CO) at a rate of 1% v/v.

Visual weed control evaluations for yellow nutsedge, hemp sesbania, Indian jointvetch, Texasweed, and alligatorweed were recorded as a percent, with 0 = no control and 100 = complete plant death at 14, 28, and 42 days after treatment (DAT). PVL01 rice plant height was recorded from four plants in each plot measured from the ground to the tip of the extended panicle (data not shown). The center four rows of rice were harvested with a Mitsubishi VM3 (Mitsubishi Corporation, 3-1, Marunouchi 2- chome, Chiyoda-ky, Tokyo, Japan) plot combine and grain yield was adjusted to 12% moisture.

Data were arranged as repeated measures and subject to the MIXED procedure of SAS (release 9.4, SAS Institute, Cary, NC). Year, replications (nested within treatments), and all interactions containing any of these effects were considered random effects. Herbicide treatment and evaluation timing were considered fixed effects. Considering year or combination of years as a random effect accounts for different environmental conditions each year having an effect on herbicide treatments for that year (Carmer et al. 1989; Hager et al. 2003). Type III statistics were used to test possible interactions of fixed effects using the UNIVARIATE procedure of SAS and significant normality problems were not observed. Tukey's honestly significant difference test was used to separate means at the 5% probability level ($P \leq 0.05$).

Table 6.1. Herbicide information for all products used in experiment[a]

Herbicide common name	Herbicide trade name	Preharvest interval[b]	Manufacturer
Floypyrauxifen-benzyl	Loyant	60	Corteva Agriscience, Indianapolis, IN
Halosulfuron	Permit	48	Gowan Company, Yuma, AZ
Halosulfuron + thifensulfuron	Permit Plus	48	Gowan Company, Yuma, AZ
Halosulfuron + prosulfuron	Gambit	48	Gowan Company, Yuma, AZ
Orthosulfamuron	Strada	40	Nichino America Inc., Wilmington, DE
Orthosulfamuron + quinclorac	Strada XT	40	Nichino America Inc., Wilmington, DE

[a]All treatments were applied with methylated seed oil (MSO; Leci-Tech, Loveland Products, Loveland, CO) at 1169 ml ha^{-1}.

[b]Preharvest interval is the minimum number of days prior to harvest which the herbicide can be applied

Results and Discussion

A salvage herbicide application by evaluation date interaction occurred for yellow nutsedge control (Table 6.2). At 42 DAT, yellow nutsedge control was 98% when treated with halosulfuron, the standard salvage treatment for sedge and broadleaf weeds in Louisiana. A similar response was observed when treated with both rates of florpyrauxifen, halosulfuron plus thifensulfuron, and both rates of halosulfuron plus prosulfuron. In addition, similar activity on yellow nutsedge was observed at 28 DAT when treated with the high rate of florpyrauxifen, halosulfuron, and the high rate of halosulfuron plus prosulfuron. These data indicate florpyrauxifen and halosulfuron plus prosulfuron will have similar activity to halosulfuron on yellow nutsedge, which is one of the most frequently used herbicides in rice for sedge control due to high levels of activity (Tehranchian et al. 2015). Trader et al. (2008) reported similar activity for yellow nutsedge treated with halosulfuron at 27 g ha^{-1}.

Table 6.2. Control for yellow nutsedge treated in a salvage situation at 14, 28, and 42 DAT in 2017 and 2018[a].

Herbicide	Rate	Yellow nutsedge control[b] 14 DAT	28 DAT	42 DAT
	g ai ha^{-1}	%		
Floypyrauxifen-benzyl	14.5	69 d-j	77 b-f	87 ab
Floypyrauxifen-benzyl	29	76 b-g	89 ab	99 a
Halosulfuron	53	75 b-h	85 abc	98 a
Halosulfuron + thifensulfuron	53	68 d-j	79 b-e	98 a
Halosulfuron + prosulfuron	55	63 f-j	71 c-i	86 abc
Halosulfuron + prosulfuron	83	78 b-f	85 abc	99 a
Orthosulfamuron	94	60 jk	67 d-j	44 l
Orthosulfamuron + quinclorac	490	59 jkl	61 g-j	67 d-j

[a]Means followed by a common letter do not significantly differ at P=0.05 using Tukey's test.
[b]Control was measured using a scale of 0 = no control and 100= complete plant death based on visual symptoms.

The standard salvage treatment of halosulfuron at 53 g ha^{-1} only controlled Texasweed 7 to 22% across all rating dates. The application of orthosulfamuron controlled Texasweed 74% at 42 DAT. This control was similar to Texasweed treated with orthosulfamuron plus quinclorac at 42 DAT and both orthosulfamuron-containing herbicides at 28 DAT. Once Texasweed reaches the 4-leaf growth stage, herbicides in group 14, or protoporphyrinogen oxidase-inhibiting herbicides are required for late season management of this weed (Eric Webster, LSU AgCenter F. Avalon Daggett Professor of Rice Research, personal communication). Carfentrazone (Aim® Herbicide, FMC Corporation: Philadelphia, PA) can be applied up to 3 days prior to rice harvest; however, aciflourfen (Ultra Blazer® Herbicide, UPL NA Inc., King of Prussia, Pennsylvania) cannot be applied later than 50 days prior to harvest.

Table 6.3. Control for Texasweed treated in a salvage situation at 14, 28, and 42 DAT in 2017 and 2018[a].

		Texasweed control		
Herbicide	Rate	14 DAT	28 DAT	42 DAT
	g ai ha^{-1}	%		
Floypyrauxifen-benzyl	14.5	6 k	6 k	4 k
Floypyrauxifen-benzyl	29	10 jk	9 jk	12 jk
Halosulfuron	53	22 hij	14 ijk	7 jk
Halosulfuron + thifensulfuron	53	29 hi	31 fgh	9 jk
Halosulfuron + prosulfuron	55	34 e-h	49 cde	21 h-k
Halosulfuron + prosulfuron	83	39 efg	55 bcd	32 fgh
Orthosulfamuron	94	46 def	64 abc	74 a
Orthosulfamuron + quinclorac	490	36 e-g	59 a-d	65 ab

[a]Means followed by a common letter do not significantly differ at P=0.05 using Tukey's test.
[b]Control was measured using a scale of 0 = no control and 100= complete plant death based on visual symptoms.

Similar to yellow nutsedge and Texasweed control, a salvage herbicide application by evaluation date interaction occurred for alligatorweed control (Table 6.4). Alligatorweed control was 99% at 42 DAT when treated with florpyrauxifen at 29 g ha^{-1}. Similar control was observed with florpyrauxifen applied at 14.5 g ha^{-1} and 29 g ha^{-1} at 14 and 28 DAT. The use of halosulfuron plus prosulfuron achieved similar control, but activity was slowed to 28 DAT. Similarly, orthosulfamuron plus quinclorac resulted in slower activity but could be an option for late season alligatorweed control. The use of the standard halosulfuron at 53 g ha^{-1} as a salvage

Table 6.4. Control for Alligatorweed treated in a salvage situation at 14, 28, and 42 DAT in 2017 and 2018[a].

Herbicide	Rate	Alligatorweed control 14 DAT	28 DAT	42 DAT
	g ai ha^{-1}	%		
Floypyrauxifen-benzyl	14.5	84 a-d	91 ab	91 ab
Floypyrauxifen-benzyl	29	88 a-d	98 a	99 a
Halosulfuron	53	19 k	21 k	24 jk
Halosulfuron + thifensulfuron	53	30 jk	50 hi	57 f-i
Halosulfuron + prosulfuron	55	64 e-h	77 cde	84 a-d
Halosulfuron + prosulfuron	83	79 b-e	92 ab	93 ab
Orthosulfamuron	94	41 ij	72 c-f	70 d-g
Orthosulfamuron + quinclorac	490	54 ghi	89 abc	89 abc

[a]Means followed by a common letter do not significantly differ at P=0.05 using Tukey's test.
[b]Control was measured using a scale of 0 = no control and 100= complete plant death based on visual symptoms.

Table 6.5. Control for Hemp Sesbania treated in a salvage situation at 14, 28, and 42 DAT in 2017 and 2018[a].

Herbicide	Rate	Hemp sesbania control 14 DAT	28 DAT	42 DAT
	g ai ha^{-1}	%		
Floypyrauxifen-benzyl	14.5	97 a	99 a	98 a
Floypyrauxifen-benzyl	29	98 a	99 a	98 a
Halosulfuron	53	94 ab	99 a	98 a
Halosulfuron + thifensulfuron	53	96 ab	98 a	98 a
Halosulfuron + prosulfuron	55	94 ab	98 a	98 a
Halosulfuron + prosulfuron	83	97 a	99 a	98 a
Orthosulfamuron	94	85 b	99 a	97 a
Orthosulfamuron + quinclorac	490	93 ab	98 a	96 ab

[a]Means followed by a common letter do not significantly differ at P=0.05 using Tukey's test.
[b]Control was measured using a scale of 0 = no control and 100= complete plant death based on visual symptoms.

treatment controlled alligatorweed 19 to 24 % across all rating dates and will require other herbicide options if this weed is present.

Similar to yellow nutsedge, Texasweed, and alligatorweed control, a salvage herbicide application by evaluation date interaction occurred for hemp sesbania control (Table 6.5). At 14 DAT, hemp sesbania control was greater than 93% when treated with each herbicide at salvage except orthosulfamuron with 85% control. At 28 and 42 DAT, hemp sesbania control was greater than 96% when treated with each herbicide at salvage, suggesting all of the herbicides evaluated can be beneficial tools in a salvage situation when hemp sesbania is present. Miller and Norsworthy (2018a) reported similar activity when hemp sesbania was treated with florpyrauxifen, 2,4-D, triclopyr, and aciflourfen. The response of Indian jointvetch (Table 6.6), a close relative to hemp sesbania, was similar to hemp sesbania control for each herbicide treatment across all evaluations.

Table 6.6. Control for Indian jointvetch treated in a salvage situation at 14, 28, and 42 DAT in 2017 and 2018[a].

		——— Indian jointvetch control ———		
Herbicide	Rate	14 DAT	28 DAT	42 DAT
	g ai ha^{-1}	——————— % ———————		
Floypyrauxifen-benzyl	14.5	97 a	97 a	98 a
Floypyrauxifen-benzyl	29	98 a	99 a	98 a
Halosulfuron	53	93 ab	98 a	97 a
Halosulfuron + thifensulfuron	53	95 a	98 a	98 a
Halosulfuron + prosulfuron	55	93 ab	98 a	97 a
Halosulfuron + prosulfuron	83	96 a	99 a	98 a
Orthosulfamuron	94	81 b	98 a	97 a
Orthosulfamuron + quinclorac	490	94 a	98 a	96 a

[a]Means followed by a common letter do not significantly differ at P=0.05 using Tukey’s test.
[b]Control was measured using a scale of 0 = no control and 100= complete plant death based on visual symptoms.

PVL01 rice injury was less than 5% across all evaluations (data not shown). Rough rice yield for PVL01 treated with orthosulfamuron at was 5510 kg ha^{-1} (Table 6.7). A similar yield response was observed for rice treated with florpyrauxifen at 29 g ha^{-1}, halosulfuron plus prosulfuron at 55 or 83 g ha^{-1}, halosulfuron plus thifensulfuron at 53 g ha^{-1}, or orthosulfamuron plus quinclorac at 490 g ha^{-1}, indicating the potential for use in a salvage situation. However, yield for nontreated PVL01 rice was 3370 kg ha^{-1}, similar to rice treated with halosulfuron. This yield reduction is likely due to little to no halosulfuron activity on Texasweed and alligatorweed; therefore, halosulfuron should be avoided or prosulfuron or thifensulfuron should be added to halosulfuron in a salvage situation where these weeds are present.

Table 6.7. Rough rice yield for 'PVL01' rice treated with each herbicide in a salvage situation in 2017 and 2018[a].

Herbicide	Rate	kg ha^{-1}
	g ai ha^{-1}	
Nontreated	—	3370 c
Floypyrauxifen-benzyl	14.5	4170 bc
Floypyrauxifen-benzyl	29	5070 ab
Halosulfuron	53	3350 c
Halosulfuron + thifensulfuron	53	5030 ab
Halosulfuron + prosulfuron	55	4540 abc
Halosulfuron + prosulfuron	83	5170 ab
Orthosulfamuron	94	5510 a
Orthosulfamuron + quinclorac	490	4330 abc

[a]Means followed by a common letter do not significantly differ at P=0.05 using Tukey's test.

In conclusion, salvage situations should be avoided in rice production; however, it is understood that these situations can occur and weed control will be problematic (Bond and Walker 2012). Florpyrauxifen will be a beneficial tool in a salvage situation when large yellow nutsedge, alligatorweed, hemp sesbania, and Indian jointvetch are present, but should be avoided with an infestation of Texasweed. In addition, the higher rate of florpyrauxifen at 29 g ha^{-1} should be used in a salvage situation to avoid rice yield loss. Halosulfuron plus prosulfuron could also provide a beneficial tool that can used at either 55 or 83 g ha^{-1} without a negative impact on yield; however, the higher rate should be used when alligatorweed is present. In addition, this product also has activity on Texasweed, unlike florpyrauxifen. Halosulfuron applied alone should be avoided when larger weeds are present in a salvage situation.

Chapter 7
Summary

Florpyrauxifen-benzyl (florpyrauxifen) was released by Corteva Agriscience in™ 2018 for commercial postemergence use in rice and crawfish production (Anonymous 2017). As a member of the arylpicolinate family, florpyrauxifen has different plant binding characteristics than other synthetic auxin herbicides; therefore, represents a novel mechanism of action with activity on a broad spectrum of grass, broadleaf, and sedge weeds (Bell et al. 2015; Miller and Norsworthy 2018a). In plants, florpyrauxifen must be converted to florpyrauxifen-acid via enzymatic hydrolysis; therefore, soil moisture can have a major impact on florpyrauxifen on florpyrauxifen absorption and conversion to the active acid form, especially when grass and sedge weeds are present (Epp et al. 2016; Miller and Norsworthy 2018b).

Flooding rice has historically been a beneficial weed control tool (Helms 1994; Masson et al. 2001); however, in dry-seeded rice, situations often arise where an early season weed control approach may fail prior to flooding (Bond and Walker 2012). Postflood weed control, commonly referred to as salvage, can be problematic due to the advanced growth stages of target weeds and poor herbicide spray coverage as a result of the developing rice and weed canopy (Bond and Walker 2012; Webster 2014). With florpyrauxifen having increased activity under high soil moisture conditions, investigation is needed evaluate the herbicide’s activity in a salvage situation.

Water-seeded rice (*Oryza sativa* L.) accounts for approximately 35% of the rice planted in Louisiana (Harrell 2016). In addition, rice production in Louisiana is often rotated with crawfish [*Procambarus clarkii* (Girard); *Procambarus zonangulus* (Hobbs & Hobbs)] production (McClain and Romaire 2004). Coupled with water seeding, these rice-crawfish rotations result in extended field flood inundation periods; thus, creating a more favorable environment for aquatic weed growth development, and interference (Jackson and Colmer 2005; McKnight 2017; Webster 2014). Lack of tillage can also contribute to the shift from annual grass and broadleaf weeds to perennial aquatic weeds (Webster 2014). Since florpyrauxifen activity increases with soil moisture, research is needed to evaluate the activity the herbicide when applied at different rates on aquatic weeds.

Herbicide mixtures are an integral component of weed management programs with regards to improving herbicide activity, broadening the weed control spectrum, and maximizing yield and economic returns (Carlson et al. 2011; Pellerin et al. 2003; Pellerin and Webster 2004; Webster et al. 2012). However, herbicides with grass activity are often antagonized when applied in a mixture with other herbicides (Rustom et al. 2018, 2019; Scherder et al. 2005; Webster et al. 2019; Zhang et al. 2005). Therefore, understanding florpyrauxifen interactions with other herbicides is necessary before utilizing this new product mixed with another herbicide.

A field study was conducted in 2018 at two locations at the H. Rouse Caffey Rice Research Station (RRS) near Crowley, LA, to evaluate the activity of titrated rates of florpyrauxifen on aquatic weeds commonly found in rice and crawfish production. Aquatic weeds were transplanted into 91-cm diameter by 30-cm tall galvanized rings that were pressed firmly into the soil 5-cm. Flooding in the research area simulated a water-seeded pinpoint flooding system. Visual weed control ratings were recorded at 14, 28, 42, and 56 days after treatment (DAT). In addition, each weed was hand harvested at 56 DAT for fresh weight biomass evaluation.

A herbicide application main effect occurred for alligatorweed and ducksalad control; therefore, data were averaged over evaluation timings. Alligatorweed control was 98% when treated with florpyrauxifen at the highest rate of 29.5 g ha^{-1} and this response was similar when alligatorweed was treated with 25.6, 22, and 18.6 g ha^{-1}. However, alligatorweed control was reduced when treated with florpyrauxifen at 3.6 to 14.3 g ha^{-1}. These data indicate the rate of florpyrauxifen can be reduced to 18.6 g ha^{-1} for alligatorweed management without a negative impact on control. Ducksalad control was 89 to 99% when treated with all rates of florpyrauxifen at 11 to 29.5 g ha^{-1}; however, control was reduced to 51 to 79% when treated with rates lower than 11 g ha^{-1}. A similar trend was observed when ducksalad fresh weight biomass was reduced 91 to 99% when treated with florpyrauxifen at 11 to 29.5 g ha^{-1}. These data suggest the florpyrauxifen rate can be reduced to 11 g ha^{-1} to manage ducksalad.

A herbicide application rate by evaluation timing interaction occurred for cattail, creeping water primrose, grassy arrowhead, and pickerelweed control. At 56 DAT, cattail control was 79% when treated with florpyrauxifen at 22 g ha^{-1}, similar to what was observed when treated with florpyrauxifen at 29.5 g ha^{-1}. A similar response was observed for cattail biomass for rates higher than 22 g ha^{-1}. Control for creeping water primrose did not exceed 50% at any evaluation timing, suggesting florpyrauxifen only suppresses this weed at rates higher than 22 g ha^{-1}. Grassy arrowhead control was above 87% at all DAT when treated with florpyrauxifen at 11 g ha^{-1} and higher. A similar response was observed when grassy arrowhead fresh weight biomass was reduced by 91 to 99% when treated with all rates between 11 and 29.5 g ha^{-1}. At 56 DAT, pickerelweed control was 99% when treated with florpyrauxifen at 29.5 g ha^{-1} and similar to pickerelweed treated with 14.3 g ha^{-1} or higher. A similar response was observed when pickerelweed biomass was reduced by 86 to 99% when treated with florpyrauxifen at the same rates.

Field studies were conducted at the RRS in 2017 and 2018 to evaluate the mixture interactions of florpyrauxifen mixed with graminicides, ALS-inhibiting herbicides, and contact herbicides commonly used in rice production. The studies were conducted two times each. Plot size was 1.5 by 5.2 m with eight-19.5 cm drill-seeded rows planted with ‘PVL01’ rice at a rate of 67 kg ha^{-1}. Visual weed control was recorded at 14, 28, and 42 DAT. Additionally, PVL01 rough rice yield was also recorded.

For the study evaluating florpyrauxifen mixed with graminicides, little to no antagonism was observed for barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv], yellow nutsedge (*Cyperus esculentus* L.), rice flatsedge (*Cyperus iria* L.), Indian jointvetch (*Aeschynomene* indica L.), or hemp sesbania [*Sesbania herbacea* (Mill.) McVaugh] control. In addition, rice treated with each mixture indicated higher yields than rice treated with each of the products applied alone. These data suggest cyhalofop, fenoxaprop, and quizalofop can be beneficial mix partners with florpyrauxifen.

For the ALS mixture interaction study, barnyardgrass activity was antagonized when treated with florpyrauxifen mixed with all ALS-inhibiting herbicides at 14 DAT. Bensulfuron, bispyribac, halosulfuron, imazosulfuron, orthosulfamuron, orthosulfamuron plus quinclorac, and penoxsulam at 14 DAT. By 42 DAT, the antagonistic response for barnyardgrass control persisted for all treatments, except when treated with florpyrauxifen plus bensulfuron or imazosulfuron, which indicated a neutral response. In addition, rice flatsedge activity was antagonized when treated with all mixtures at 14 DAT; however, this antagonism was overcome by 28 DAT. In addition, little to no antagonism was observed for Indian jointvetch or hemp sesbania control at all evaluation timings. PVL01 rough rice yield was reduced wen treated with florpyrauxifen mixed with orthosulfamuron; however, yield was similar to rice treated with florpyrauxifen applied alone for all other mixtures.

Similar to the ALS study, all of the herbicides evaluated antagonized florpyrauxifen activity on barnyardgrass at 42 DAT in the contact herbicide study. The expected barnyardgrass control when treated with florpyrauxifen mixed with bentazon, carfentrazone, propanil, saflufenacil, or thiobencarb each mixture was 79 to 89%. In comparison, the observed control was reduced to 32 to 67% when treated with each mixture, indicating contact herbicides should be avoided in mixtures with florpyrauxifen when barnyardgrass is present. However, at 42 DAT, no antagonism was observed when yellow nutsedge, rice flatsedge, Indian jointvetch, or hemp sesbania was treated with each mixture, suggesting contact herbicides can be used in a mixture with florpyrauxifen when these weeds are present. PVL01 rice yield was reduced when treated with all mixtures, except florpyrauxifen plus carfentrazone, the only mixture that was not antagonistic for barnyardgrass control at 14 or 28 DAT.

A field study was conducted at the RRS in 2017 and 2018 evaluate the activity of florpyrauxifen or halosulfuron plus prosulfuron when applied at two different rates in a salvage situation, compared with halosulfuron, which is the standard sedge and broadleaf treatment in Louisiana. Plot size was 1.5 by 5.2 m with eight-19.5 cm drill-seeded rows planted with ‘PVL01’ rice at a rate of 67 kg ha^{-1}. Herbicide treatments were applied at salvage when rice was 3- to 4-tiller and approaching panicle initiation. Visual weed control was recorded at 14, 28, and 42 DAT. Additionally, PVL01 rough rice yield was also recorded.

A salvage herbicide application by evaluation date interaction occurred for yellow nutsedge control. At 42 DAT, yellow nutsedge control was 98% when treated with halosulfuron, the standard salvage treatment for sedge and broadleaf weed in Louisiana. A similar response was observed when treated with both rates of florpyrauxifen, halosulfuron plus thifensulfuron, and both rates of halosulfuron plus prosulfuron. In addition, similar activity on yellow nutsedge was observed at 28 DAT when treated with the high rate of florpyrauxifen, halosulfuron, and the high rate of halosulfuron plus prosulfuron. These data indicate florpyrauxifen and halosulfuron plus prosulfuron will have similar activity to halosulfuron on yellow nutsedge.

Similar to yellow nutsedge control, a salvage herbicide application by evaluation date interaction occurred for alligatorweed control. Alligatorweed control was 99% at 42 DAT when treated with florpyrauxifen at 29 g ha^{-1}. Similar control was observed with florpyrauxifen applied at 14.5 g ha^{-1} and 29 g ha^{-1} at 14 and 28 DAT. The use of halosulfuron plus prosulfuron achieved similar control, but activity was slowed to 28 DAT. The use of the standard halosulfuron at 53 g ha^{-1} as a salvage treatment controlled alligatorweed 19 to 24 % across all rating dates and will require other herbicide options when alligatorweed is present.

In conclusion, florpyrauxifen will be a beneficial tool allowing producers to control a broad spectrum of grass, broadleaf, and sedge weeds. Rotating crops and modes of action has proven to be a beneficial practice for weed management (Norsworthy et al. 2012), and florpyrauxifen represents a new mechanism for postemergence use in both rice and crawfish production. In addition, this herbicide must have increased soil moisture to maximize activity on grass and sedge weeds (Miller and Norsworthy 2018b).

The florpyrauxifen activity observed in these studies will be beneficial to producers in developing weed management strategies to effectively utilize this new technology and improve economic returns. The activity of reduced rates of florpyrauxifen can have similar activity to the maximum labeled rate when applied on several aquatic weeds; therefore, can improve economic returns for producers. All of the ALS-inhibiting or contact herbicides evaluated antagonized florpyrauxifen activity on barnyardgrass, indicating producers should avoid applying these products in a mixture with florpyrauxifen to maximize the herbicide's activity on this weed.

However, little to no antagonism was observed for weeds treated with florpyrauxifen mixed with graminicides, indicating these products can be used in a mixture to improve the weed control spectrum. Florpyrauxifen will be a beneficial tool in a salvage situation where large yellow nutsedge, alligatorweed, hemp sesbania, and Indian jointvetch are present, but should be avoided with an infestation of Texasweed. Similarly, halosulfuron plus prosulfuron will also be a beneficial tool in a salvage situation.

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Vita

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